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MIXED U/Pu OXIDE FABRICATION FACILITY FOR GEL-
SPHERE-PAC FUEL

CO-CHAIRMEN/WG.4/40 (B)
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MIXED URANIUM-PLUTONIUM OXIDE FABRICATION FACILITY FOR GEL-SPHERE-PAC FUEL

CONTENTS

GEL-SPHERE-PAC PLANT DESCRIPTION

1. The fuel element design is comparable to a current Pressurized Water Reactor element of the Westinghouse Design.
2. The plant production capacity is 200 MT of HM/yr with simultaneous production of three enrichments.
3. Effective full production days per year are 240.*
4. Plant design capacity:

Overall	300 MT of HM/yr
	∿2 fuel assemblies/day
Each line	100 MT of HM/yr
(3 total)	0.28 MT of HM/day
	158 fuel rods/day
	0.6 fuel assembly/day

5. Process design capacities are based on the line design capacities and the scrap and sample losses defined in Table 3.1.
6. The facilities shall be designed to have no liquid wastes discharge other than treated sanitary sewage.
7. All process buildings and critical auxiliary support shall be designed and constructed in accordance with current United States Nuclear Regulatory Commission licensing requirements. Shielding is provided to limit dose rates to operating and maintenance personnel to 0.25 mR/hr.

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*240 effective full production days is equivalent to 250 working days used in other reports.

I. INTRODUCTION

This report is one of a series of reports on the subject of plutonium recycle in Light Water Reactors (LWRs) being prepared for the International Nuclear Fuel Cycle Evaluation (INFCE) Working Group 4. One of the goals of this working group is to assess plutonium recycle in LWRs. Other reports will focus on preparation of mixed uranium-plutonium oxide fuel by pellet processes. The reference process is considered to be pellet fabrication using separated oxides.

This report will focus on the use of the Gel-Sphere-Pac process for fabrication of the mixed $(U,Pu)O_2$ fuel. Two basic cases will be covered in the body of the report: (1) fabrication of coprocessed $(U,Pu)O_2$, and (2) fabrication of coprocessed spiked $(U,Pu)O_2$. The former requires a plant which operates remotely but permits contact maintenance. The latter requires a plant which is both remotely operated and maintained. The coprocessed plant is described as the base case, and changes to this plant which are necessary to prepare coprocessed-spiked $(U,Pu)O_2$ fuel are described.

The Gel-Sphere-Pac process[1-5] utilizes high-density spheres of the required fuel, which are loaded into the fuel cladding by low-energy vibration, to give a high-density (∿85–88%T.D.*) fuel rod. Preparation of dry gel spheres is assumed to occur at the reprocessing plant during the product conversion step for the fissile $(U,Pu)O_2$ material. This step can be carried through calcination at the reprocessing plant if desired. This process is called Sphere-Conversion and is described in Appendix A. Dry gel-fissile spheres are received at the fuel fabrication plant where they are calcined, sintered to high density (>98%T.D.), and loaded into fuel rods along with UO_2 fertile fine spheres. The sintered fine UO_2 spheres are purchased from a cold fabrication plant ready for use; this fabrication process is very similar to that described in Appendix A for larger spheres.

The Sphere-Pac process requires three size fractions to produce high-density fuel rods. Therefore, the fissile $(U,Pu)O_2$ spheres are prepared in large coarse (nominal 1200-μm diameter) and small coarse (nominal 300-μm diameter) sizes. The fertile fine UO_2 spheres are prepared with a nominal diameter of 40 μm and provide about 20% of the total heavy metal.

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*% of theoretical density.

2. DEFINITION OF THE GEL-SPHERE-PAC LWR PLUTONIUM RECYCLE FUEL FABRICATION PLANT

The plant design concept presented in this paper addresses only those processes directed toward the fabrication of fuel assemblies containing (U-Pu)O_2 designed for use in a light water reactor. The processes are limited to the production of sintered (U,Pu)O_2 microspheres, loading of fuel rods, assembly of these rods into a finished assembly and the supporting activities necessary to perform these steps in a safe licensable commercial facility. Since this refabrication plant is an integral part of the overall fuel cycle, it must interface with other activities within the cycle and is supported by external sources of supplies and materials. Figure 2.1 shows both the primary external process interfaces and some of the supporting activities within the plant.

The Sphere-Pac process is dependent on the Reprocessing Plant conversion product for its primary fuel component input. This feed material, however, differs in form from the pellet process. The reference pellet process utilizes dry powders of uranium and plutonium which are subsequently blended and conditioned for process feed within the fabrication plant. The Sphere-Pac process utilizes free-flowing spherical particles of homogeneous (U,Pu)O_2 which are formed in the product conversion process step (see Appendix A) of the Reprocessing Plant as process feed. The (U,Pu)O_2 spheres are obtained in two sizes, large coarse (nominal 1200-μm diam) and small coarse (nominal 300-μm diam). In addition, a third size microspheres (fertile fine) is utilized in the process. This is natural (or depleted) UO_2 in the form of very small (nominal 40-μm diam), dense microspheres, which can be produced within an auxiliary process support activity in the refabrication plant or purchased from a supplier as shown in Fig. 2.1. Hardware components such as fuel rod cladding and material for the assembly skeletons are also purchased from outside suppliers.

Within the primary processing operation, there will be material rejected by the quality control inspection functions. For the Sphere-Pac process it is estimated that this rejected material will be from two main sources: the microsphere inspection step of Fig. 3.3 and the fuel rod loading process shown in Fig. 3.4. The material rejected during fuel rod loading will be internally recyclable with a minimum amount of rework

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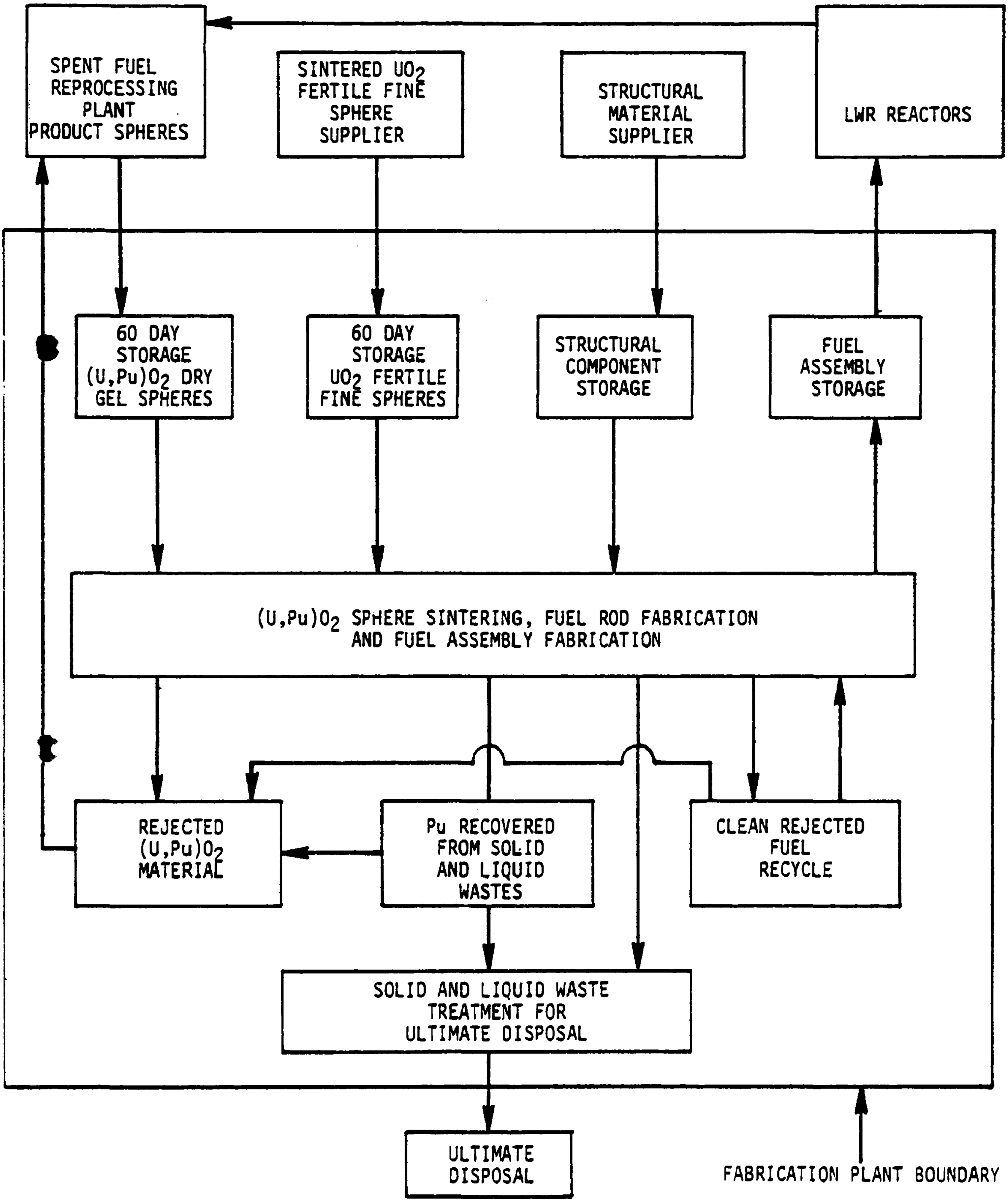

Fig. 2.1. LWR Recycle Pu Fuel Fabrication Plant.

(i.e., only size classification). The material rejected during microsphere inspection step will be collected, weighed, assayed, and returned to the reprocessing plant for recycle. In addition to this clean scrap there will be contaminated materials, both solid and liquid, which must be treated for ultimate disposal. Such treatment will include processing to recover plutonium, where possible, volume reduction and conversion of the remaining waste to a form suitable for ultimate disposal.

2.1 Operating Philosophy

The operational philosophy for these facilities was based on two assumptions: (1) for coprocessed fuel, a remotely operated-contact maintained facility was assumed, which with moderate shielding between process stations, would permit personnel access after all material in-process was removed from the station to be maintained, and (2) for spiked fuel material, a remotely operated, remotely maintained facility was assumed.

In other respects both plants are to be operated on a three-shift-per-day, 7-day-per-week basis. Both operating and maintenance personnel are available on all four shift crews, although there will be some increases in the day shift complement 5 days a week. Administration and engineering personnel are involved only for day-shift operation 5 days per week.

All process operations in both facilities are to be mechanized for remote control by the operators. All fuel materials recovered in the waste treatment process will be recovered as a mixed uranium-plutonium product and converted to a solid oxide before return to the reprocessing plant.

2.2 In-Process Inventory Requirements

A total in-process inventory assessment was made of the refabrication plants on the assumption that all three fuel pin loading lines were in full production. This is presented in Table 2.1. Examination of this table shows that with the exclusion of materials in feed storage or finished fuel element storage, only 9.6 metric tons of HM as $(U,Pu)O_2$ (5.6% Pu av) are in the process areas and only 2.9 metric tons of $(U,Pu)O_2$ (5.6% Pu av) of this is not contained in sealed fuel rods.

Table 2.1 Surge storage requirements and normal inventory

Process step	Material	Storage interval (days)		Normal inventory (kg HM)	
		Normal	Max	$(U,Pu)O_2$[a]	UO_2 fines
A. Feed Storage	Dried Spheres	30	60	20,000	
	Sintered Spheres	30	60		5000
B. Interim Storage	Dried Spheres	1	2	700	
	Sintered Spheres	1	2		200
C. Furnace	Dried to Sintered Spheres	1.2	2.4	800	
D. Post furnace	Sintered Spheres	0.5	1	400	
E. Interim Storage	Sintered Spheres	0.36	0.72	300	
F. Main Storage	Sintered Spheres	1.2	2.4	800	
	Sintered Spheres	1.5	2.9		300
G. Loading, Inspection, Welding	Sintered Spheres	0.12	0.24	80	20
H. Loaded, not inspected pins		5	5	3400	900
I. Rework-scrap	Sintered Spheres	0.12	0.24	80	20
J. Completed Fuel Rods	Sintered Spheres in Pins	5	5	3400	900
K. Assembly	Rods in Completed assemblies	15	30	10,000	2500

[a] 5.6% nominal plutonium content.

3. FABRICATION PROCESSES

The purpose of this section is to present a description for each of the four main fuel fabrication steps. These are: (1) receiving and storage, (2) fuel production, (3) fuel rod fabrication, and (4) fuel assembly fabrication. Process flowsheets are included in the discussion. In addition, a description of product control processes and scrap and waste processing and disposal is also included.

3.1 Product Manufacture

3.1.1 Flowsheet and process descriptions

A Gel-Sphere-Pac generic functional flow diagram is shown in Fig. 3.1. The main functions unique to the Gel-Sphere-Pac process are fuel productic and fuel rod fabrication. Brief process descriptions of the various functional steps are given below.

Receiving and storage. As shown in Fig. 3.2, the containers of dried gel spheres (two sizes for each of three fissile levels) of $(U,Pu)O_2$ are received from the reprocessing plant, weighed and stored. These container weights and their respective, accompanying samples are the basis of inventory control of material entering the plant. In a similar manner, the sintered spheres of normal (or depleted) UO_2 fertile fines will be received, weighed, and stored. As required by the process, a container will be sampled and held in interim storage (pneumatic transfer hopper) until analysis verifies that it is acceptable material. It will than be pneumatically transferred to fuel rod fabrication.

Fuel production. The purpose of the fuel production step is to convert the dry gel spheres to high-density sintered spheres required for Sphere-Pac loading. This is accomplished by calcination and sintering as shown in Fig. 3.3.

As material is required for fuel production, individual containers are removed from storage and passed successively through a sampler and a splitter. The splitter subdivides the batch and loads it into the furnace boats. After analysis verifies the material to be acceptable, the boats

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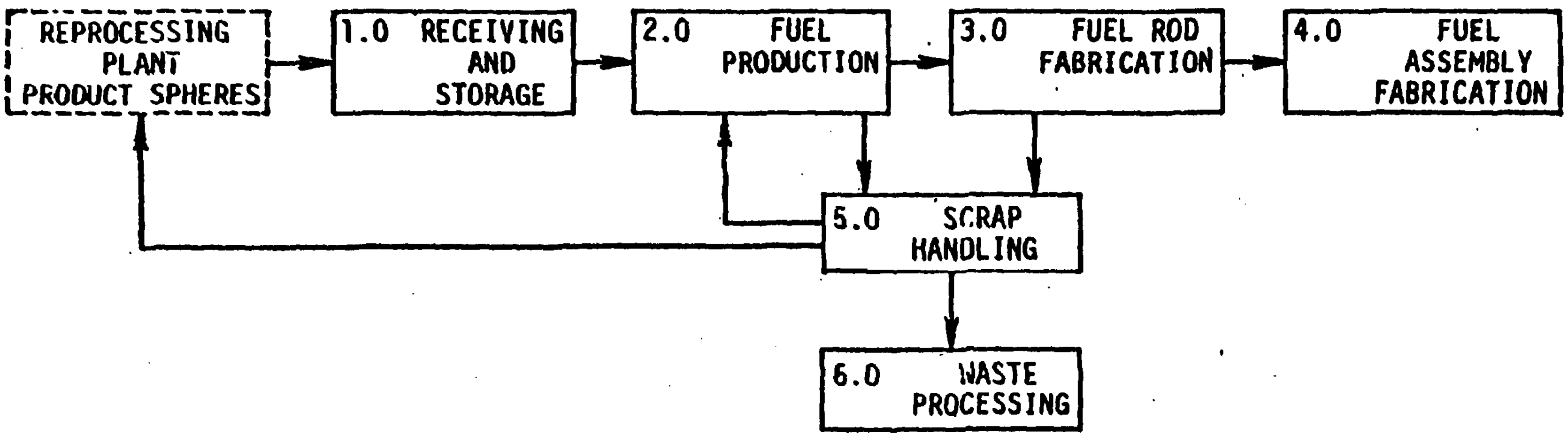

Fig. 3.1 Gel-Sphere-Pac Generic Fuel Refabrication Functional Flowsheet.

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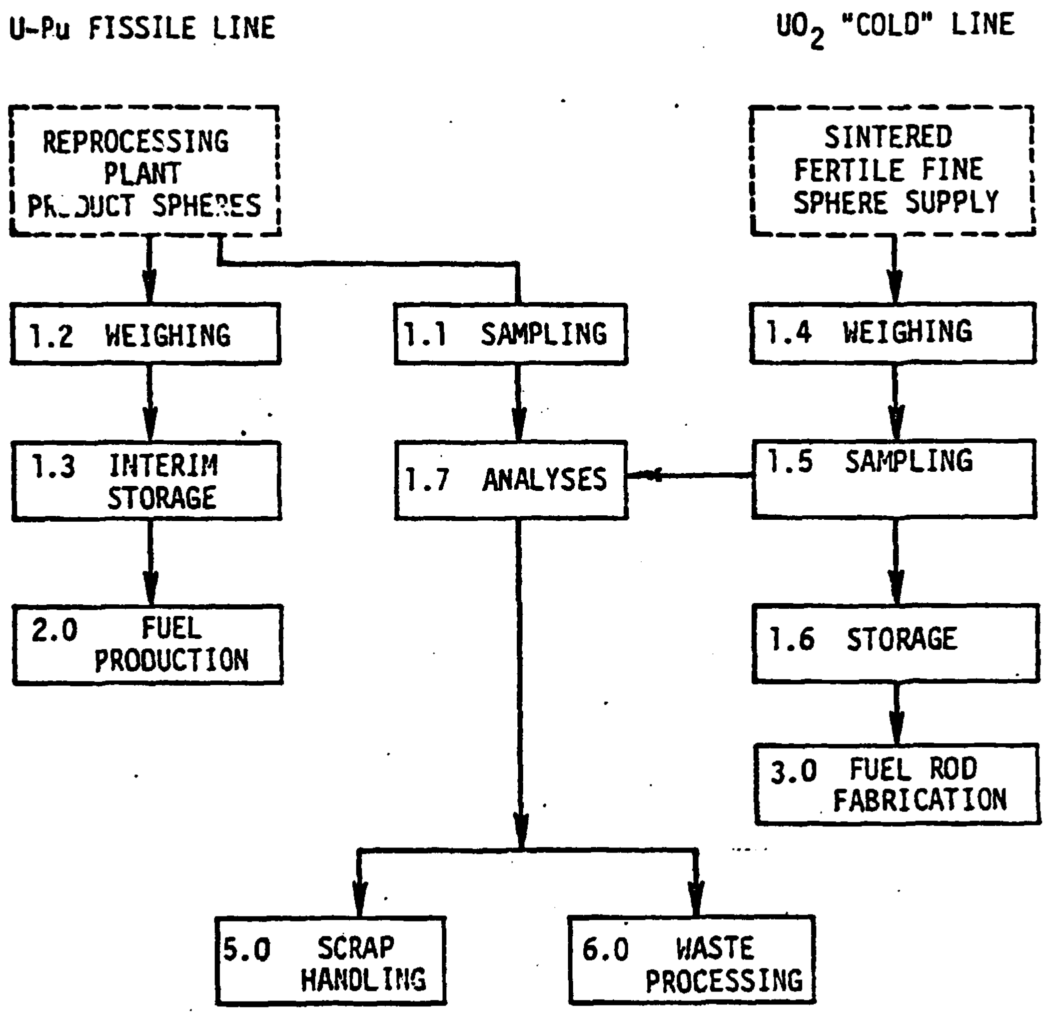

Fig. 3.2 Gel-Sphere-Pac Generic Functional Flowsheet

1.0 Receiving and Storage

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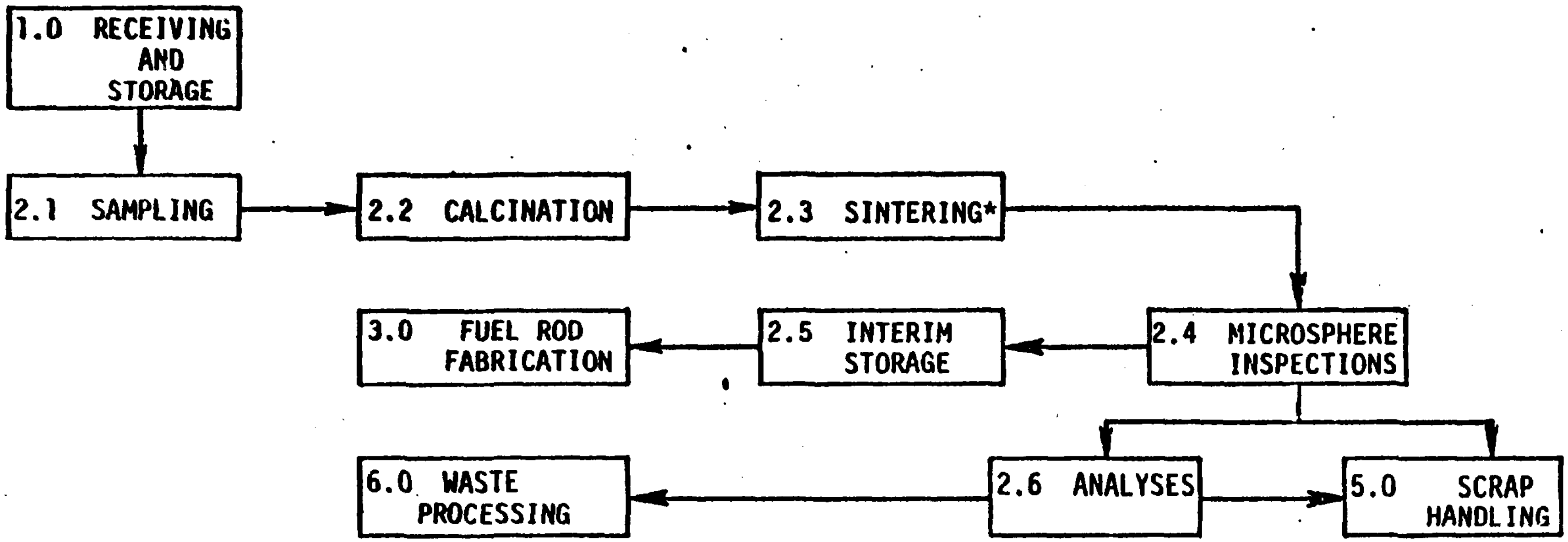

*INCLUDES O/M ADJUSTMENT

Fig. 3.3 Gel-Sphere-Pac Generic Functional Flowsheet
2.0 Fuel Production — U,Pu Fissile Stream.

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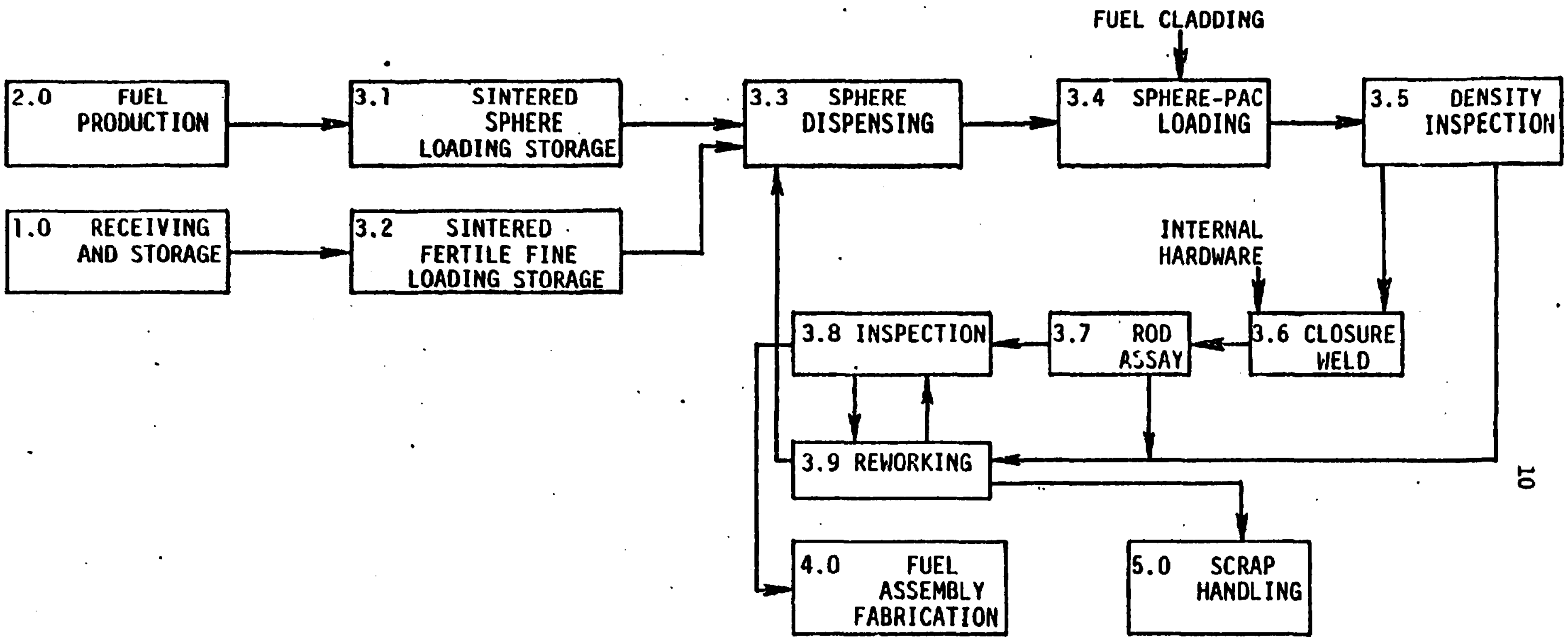

Fig. 3.4 Gel-Sphere-Pac Generic Functional Flowsheet
3.0 Fuel Rod Fabrication.

are loaded into one of the calcination-sintering furnaces. There are three main production lines (one for each assay level), each containing two furnaces.

The calcination portion of the cycle heats the particles to a moderate temperature (~500°C) in a slightly reducing atmosphere to remove the volatiles. Following calcination, the particles are reduced and sintered to a high density by continuing to heat in a reducing atmosphere to a maximum temperature in the range of 1450 to 1650°C. The as-sintered particles [now $(U,Pu)O_2$ with the oxygen/metal ratio adjusted] are cooled, unloaded, and transferred to microsphere inspection. In this step, the particles are size and shape classified, sampled, and held in interim storage (pneumatic transfer hoppers) until analyses are complete. Upon verification of acceptable material, the particles will be pneumatically transferred to fuel rod fabrication (Fig. 3.4). Reject material from size and shape classification and material not meeting specifications will be sent to scrap handling. Waste from laboratory analysis will be routed to waste processing.

Fuel rod fabrication. The main purpose of the fuel rod fabrication step is to load the high-density spheres into high-density rods using low-energy vibration. The various steps of fuel rod fabrication are shown in Fig. 3.4. The main storage hoppers receive and store acceptable, sintered spheres until needed for rod loading. There are three fuel rod loading lines, one for each of the assay levels. Each loading line has three storage hoppers for the large coarse spheres, small coarse spheres, and fines, respectively. Each hopper provides storage for 2 days of operation.

The amount of each type of microsphere needed for a fuel rod will be volumetrically dispensed from each of the three hoppers, weighed, and transferred to the respective three hoppers of the loading line. The material from all three hoppers will be simultaneously dispensed, blended, and loaded into the cladding tube. Each loading line has a single blender-feeder, which will alternately feed the three loading stations of the line by use of a rotary diverter valve. After being filled, the fuel rods will be vibrated to achieve the proper fuel column length and density.

The loaded rods will be moved to one of the two densitometer stations where both the fuel column length and the fuel density along the length will be determined. Rods that do not meet specifications are transferred to the rework station.

Fuel rods that meet specifications are advanced to the subsequent stations where the weld area is cleaned, the remaining top components (disc, spring, etc.) added, and the rod evacuated, pressurized, and welded.

The rods are then placed in a horizontal position to accommodate the final inspections. These include homogeneity and assay measurement, which determine both the amount and distribution of both fissile and fertile material using gamma-ray attenuation and neutron irradiation and detection. In addition, inspections of the mechanical integrity of the welded rod will be made. Rods that meet specifications are sent to fuel assembly fabrication (Fig. 3.5), while rods that do not meet specifications are transferred to the rework area. From the rework area, rods may be returned for reinspection or may be unloaded with the particles returning to the dispensing/loading area (following size classification) and the hardware sent to scrap handling.

Fuel assembly fabrication. Acceptable fuel rods from fuel rod fabrication are transferred to fuel assembly fabrication as shown in Fig. 3.5. The surface of the fuel rods is decontaminated and checked to ensure that it conforms to allowable contamination levels. The decontaminated fuel rod is then added to the assembly skeleton to form the completed assembly. The assembly is inspected, reworked as required, and stored in the completed assembly area. From here, the assemblies are shipped, as required, to various reactors.

3.1.2 Product control processes

To ensure the production of a high-quality product, sampling and testing will be done throughout the various process steps. This will include analyzing the as-received dried microsphere (large coarse and small coarse) for accountability purposes (heavy-metal content) and quality control (impurities). After sintering, the particles will receive a more complete analysis since the processing is complete and the particles are ready for loading. This is also true of the as-received sintered UO_2 fines since they are also ready for loading. Analysis of sintered particles includes plutonium/uranium ratio, oxygen/metal ratio, impurities, gas content, moisture content, particle size distribution, nitrogen content, etc. After the fuel rod is loaded, testing will concentrate on determining the metal content

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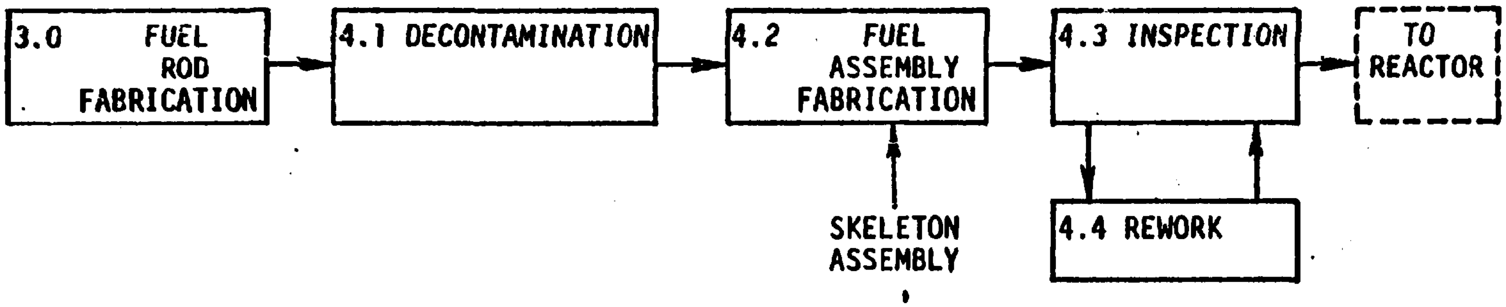

Fig. 3.5 Gel-Sphere-Pac Generic Functional Flowsheet
4.0 Fuel Assembly Fabrication.

and distribution along the fuel column length. The various samples and tests are divided into three types of controls:

1. "In-line" controls which are nondestructive controls made on 100% of the product. Once the sintered particles are loaded into the fuel cladding, essentially all of the testing will be of this type. The contents of out-of-specification rods will be returned to the system just ahead of the rod loading step.
2. "On-line" controls are statistical examinations of part of the product. Examples of these types of controls include weights, assaying gas content, moisture content, particle size distribution, and nitrogen content.
3. "Off-line" controls are statistical nondestructive and destructive controls made on part of the product. The bulk of such controls are tests on control and analytical samples that have been transported (normally by pneumatic means) to the laboratory. Examples of this type of control may include analyses of impurities and heavy-metal analysis (of particle samples and reject material, moisture content, particle density, plutonium/uranium ratio, oxygen/metal ratio, isotopic assay, etc.).

3.2 Scrap and Waste Processing and Disposal

3.2.1 Scrap handling

As shown in Fig. 2.1, three types of scrap material are generated in a sphere-pac mixed oxide fuel fabrication plant. These are: clean rejected (internal recycle), rejected (external recycle), and recoverable plutonium from solid and liquid wastes. Clean rejected material occurs when a fuel rod is rejected for failure to meet mechanical (i.e., poor weld), density, or homogeneity specifications. When this occurs, the spheres are poured out, sized, and returned to the appropriate storage container. Any degraded spheres are transferred to the second category of scrap material (rejected).

Rejected material consists of sintered spheres which fail to meet the sphere specification in some way (i.e., density too low, impurities too high, spheres broken). Rejected material is collected, assayed and shipped back to the reprocessing plant for dissolution and reconversion to gel spheres (see Fig. 3.6 for a flowsheet description).

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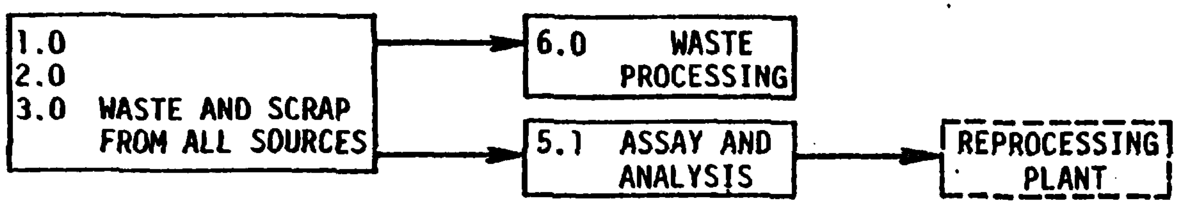

Fig. 3.6 Gel-Sphere-Pac Generic Functional Flowsheet
5.0 Scrap Handling.

The third type of scrap, recoverable plutonium from solid and liquid wastes, is separated from the solid and liquid wastes, converted to a solid oxide, and transferred to the rejected $(U,Pu)O_2$ category 2 material.

Table 3.1 provides a quantitative evaluation of expected mass flow, yield and scrap generation for the sphere-pac refabrication plants. As indicated, the quantity of clean (internally recycled) scrap anticipated is about 8%. The amount of rejected (externally recycled to the reprocessing plant) scrap is about 3%. The overall product yield is about 97%.

3.2.2 Waste processing and disposal

Waste handling and disposal is shown in Fig. 3.7. As described in Sect. 3.2.1, recoverable U,Pu is separated from waste as part of scrap recovery. However, some mixed oxide will be nonrecoverable and will be lost as waste to permanent disposal. This quantity is expected to be less than 0.25% of the total amount of plutonium treated.

Following the plutonium recovery step, aqueous wastes are concentrated and solidified while solid wastes are compacted; both are assayed and shipped for permanent disposal.

3.3 Process Changes Required for the Manufacture of Spiked Fuel

The Sphere-Pac process itself is relatively insensitive to preparing spiked vs nonspiked fuel rods. However, as described in Sect 4, more space will be needed for spiked fuel, and some equipment modification will be necessary due to the requirement for remote maintenance.

The use of spikes does affect two areas of the process: the sphere sintering and nondestructive testing devices (density, homogeneity, and assay). The high sintering temperature has the potential for removing the spike. The use of spikes will impact nondestructive devices (increased shielding, type and level of sources and detectors, energy levels, etc.) used for safeguards, and many of these methods currently in use may have to be modified.

Table 3.1 Estimated daily scrap production for a 200-MT HM/yr LWR Pu recycle fuel plant

Clean scrap[a]			Processing step and daily throughput			Reject scrap[c]		
$(U,Pu)O_2$[b] (Kg HM/day)	UO_2 fines (Kg HM/day)	(%)		$(U,Pu)O_2$[b] (Kg HM/day)	UO_2 fines (Kg HM/day)	(%)	$(U,Pu)O_2$[b] (Kg HM/day)	UO_2 fines (Kg HM/day)
			Receiving and Storage					
				689.6	166.3			
				Sampling and Batch Loading	Weighing and Sampling	0.1	0.1	0.1
				689.5	166.2			
			Calcining and Sintering			0.05	0.4	-
				689.1				
			Sphere Upgrading			3.0	20.6	-
				668.5				
			Sphere Sampling			0.2	1.3	-
				667.2				
			Sphere Storage					
				667.2	166.2			
			Fuel Rod Loading					
				667.2	166.2			
31.7	7.9	4.8	Fuel Rod Scanning			0.2	1.7	0.4
				633.8	157.9			
1.8	0.5	0.2	Top Component Insertion			0.02	0.1	0.1
				631.9	157.3			
d	d	0	Rod Welding and X-ray			0	d	d
				631.9	157.4			
d	d	0	Leak Detection			0	d	d
				631.9	157.4			
12.0	3.0	1.9	Rod Assay			0.1	0.6	0.1
				619.3	154.3			
5.9	1.4	1.0	Final Rod Inspection			0.04	0.3	0.1
				613.1	152.8			
3.0	0.8	0.5	Assembly Inspection			0.02	0.1	0.1
54.4	13.6			610	152		25.2	0.9
				54.4	13.6			
				664.4	165.6			
			830 (Total $(U,Pu)O_2$ and UO_2 fines)					

[a]Internally recycled to fuel rod loading step after size classification.

[b]5.6% average plutonium content.

[c]Collected, assayed, and externally recycled to reprocessing plant.

[d]Rework in these steps is only of the weld and does not affect scrap.

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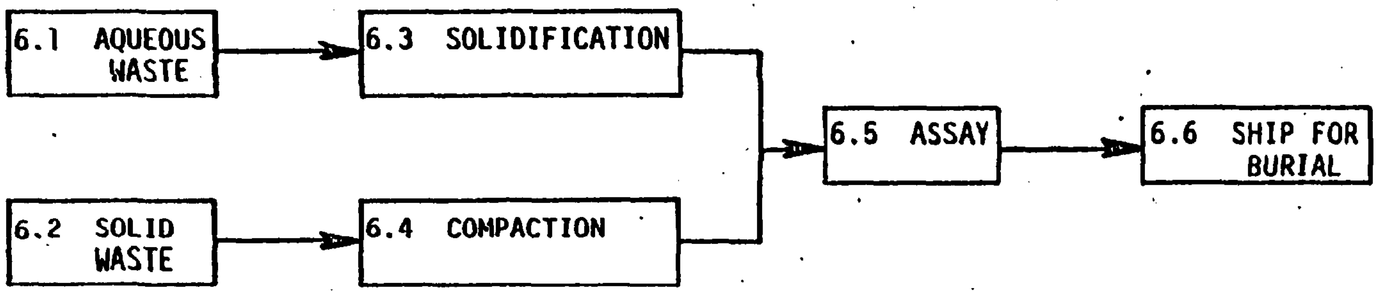

Fig. 3.7 Gel-Sphere-Pac Generic Functional Flowsheet
6.0 Waste Processing,

4. PLANT GENERAL LAYOUT AND DESCRIPTION

4.1 General Layout

A typical site plan for a refabrication plant producing 200 MT of HM product as LWR fuel elements is given in Fig. 4.1. This plan was developed to show the principal components and is not an actual concept.

All personnel access to the controlled area is through the single portal entrance. Within the controlled area are located the manufacturing process building and critical auxiliary functions. The auxiliary function areas accessible from the controlled area portal are:

1. the facility support building, which includes appropriate process material warehousing and general shops;
2. the exhaust ventilation control building (for the process building), and its associated stack;
3. the emergency electric power generation building;
4. the cooling towers;
5. various yard facilities including waste storage areas;
6. limited portions of the receiving and shipping areas associated with the process areas.

Access to the actual processing buildings is through a separate building which includes appropriate facilities for locker rooms and some operational management offices. The three process buildings provide space for:

1. the actual fuel element production,
2. the fuel element hardware manufacture and inspection together with other process support activities,
3. the treatment of all process waste.

4.2 General Description

The fuel element manufacturing processes have been described in Sect 3. In this section, attention will be focused on a description of the main process buildings.

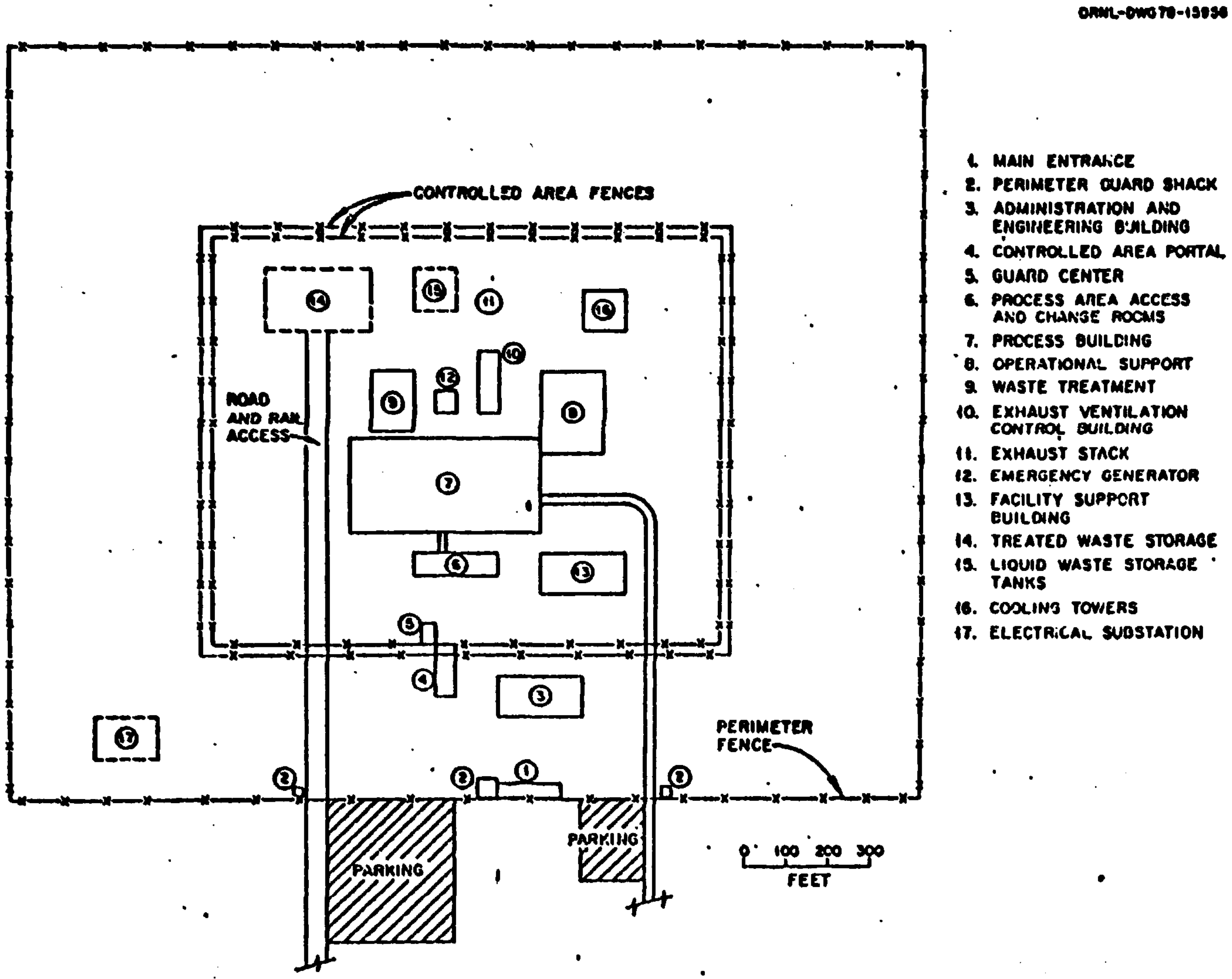

Fig. 4.1 Site Plan for a 200-MTHM/yr Sphere-Pac LWR Fabrication Plant.

4.2.1 Operational Support Building

As indicated in Sect 2, it is anticipated that most of the structural materials components in a finished fuel assembly, with the exception of the clad tubing, will be manufactured within the plant. Consequently, the Operational Support Building will house such activities as fuel cladding storage, inspection, cleaning, bottom end plug insertion and welding and loading of appropriate magazines to deliver these to the fuel fabrication area. Element assembly components will be manufactured and assembled into finished and inspected element skeletons in a separate area. Additional equipment and space is provided to test and modify, as necessary, all new fixtures and replacement equipment in order to ensure their functional performance and interface compatibility with manufacturing process area supports, utility connections, and adjacent equipment.

4.2.2 The Process Building

The Process Building houses all the actual fuel element manufacturing processes and the appropriate quality control and maintenance activities. The processing areas are physically separated by appropriate shielding walls but are remotely interconnected to provide for material movement.

The $(U,Pu)O_2$ gel spheres are received and stored in one area. Each shipment may contain several sealed containers. The identification and weight of each container are checked. They are then individually transferred through a lock to the vault storage area and placed in predetermined and monitored storage wells by remotely operated equipment. Separate transfer locks are provided for the transfer of containers to the fuel processing and rod fabrication area and to remove empty containers for return to the reprocessing plant for reuse.

The second general area includes three physically separate areas. Each area handles one of the three enrichments. These areas are designated as the fuel processing and rod fabrication area. They contain the equipment for:

1. dispensing the dried gel spheres and processing them into acceptable material for fuel rod loading,
2. actual fuel rod assembly,

3. preinspection with appropriate process surge storage, and an area for rework and internal recycle of acceptable fuel material.

All processes are conducted within confinement barriers and are remotely operated.

The third general area is the fuel element assembly area. Since only two fuel elements per day are produced at full capacity, a single manufacturing line can accommodate the output from all three fuel rod fabrication lines. Again this area is physically separated from the fuel rod fabrication area but is remotely interconnected. This separation provides additional protection against accidental contamination of the exterior surfaces of the finished assembly. The area includes surge storage for the fuel rods as received and after final inspection, as well as equipment that is needed to perform the final inspection and assay. Equipment to load the fuel rods into the assembly skeleton, inspect the assembly, and place them in a shipment support complete the contents of this area.

The final area in the direct manufacturing process line is the storage vault and shipping location for completed assemblies. This vault is similar to but smaller than the fuel-receiving storage vault. Space and equipment for loading the shipping containers and placing them on the appropriate off-site carrier are provided near the vault.

Surrounding, above, below, and adjacent to the areas in the direct manufacturing processes are areas needed for process control. These include such off-line activities as the process control operating areas and the analytical laboratories for sample analyses required for process control and product quality assurance, as well as sample analyses required to confirm plant effluent control monitoring. These areas also provide for shielding, decontamination, and confinement of contamination. Significant space is needed for process equipment maintenance. Space is also provided for process services including utilities, for material movements with limited local storage, and special ventilation equipment and controls.

4.2.3 Waste Treatment Building

The Waste Treatment Building contains both shielded and unshielded areas as required to protect operating personnel. The primary waste treatment processes in a fuel manufacturing plant involve treatment of solid wastes, both combustible and noncombustible, to reduce the volume and package the remaining materials into containers for off-site shipment and disposal. However, all liquid waste from activities within the controlled area are collected and monitored for plutonium and uranium content. Only the liquid from treated sewage is discharged from the plant. Other low contamination level liquids are evaporated for recycle to the maximum extent possible with discharge of excess waster as a vapor in the ventilation exhaust. Liquids with significant quantities of heavy-metal content are subjected to chemical processing to recover the uranium and plutonium and concentrate other contained solids and salts. These liquids include the analytical laboratory wastes, decontamination solutions and solutions derived from leaching operations, or highly contaminated wastes such as the filters as well as the concentrated low-level heels. The resulting alpha-contaminated concentrates are treated to immobilize the contents in concrete or glass. All solid waste is placed in appropriate shipping and disposal containers, assayed, and sent to treated waste storage before off-site shipment. All process equipment in the waste treatment area are contained within controlled areas to confine and test all gaseous effluents before release to the plant exhaust system and the stack.

4.3 Modifications Required for Spiked $(U,Pu)O_2$ Fabrication

Although all of the processes and general operations associated with the unspiked $(U,Pu)O_2$ fabrication apply, there are differences in the facility design and maintenance procedures.

All processing and storage for spiked fuel fabrication must be done behind heavier shielding walls, and personnel access to the main stream areas is impossible. Therefore, additional process support equipment is required to install and remove failed equipment and perform minor in situ maintenance. The repair or maintenance areas will also require heavier shielding for the work areas preceding decontamination. The main-line process equipment will require a slightly larger area to provide for remote movement and access for remote utility and control connections.

Equipment will be more complex in that the designs must accommodate the remote maintenance features, but the basic operational control and productivity rates will be the same as those of equipment designed for remote operation and contact maintenance after in-process materials are removed.

Confinement within the process equipment will be similar to that for the unspiked fuel. However, localized shielding for personnel protection during maintenance operations will not be required.

The largest operational differences will be associated with the process equipment maintenance, as described earlier, and the personnel protection in the waste-treatment and shipping areas and in the feed materials receiving and fuel elements shipping areas where very heavily shielded casks must be handled instead of the lightly shielded casks used for the unspiked fuels.

The net effect of fabricating spiked fuel will be design changes in the facility and equipment for remote maintenance.

5. PLUTONIUM CONFINEMENTS AND VENTILATION SYSTEMS

5.1 Confinement Systems

To minimize and restrict the release of plutonium-bearing materials to a level as low as practicable, confinement of plutonium-bearing materials in these plants is effected by various enclosures and the heating, ventilating, and air-conditioning (HVAC) systems which serve these enclosures. Examples of enclosures include fuel fabrication areas; hot repair cells; decontamination areas; sphere transferring equipment; storage areas; shipping containers; and the walls, floors, and ceilings of buildings and rooms. The combination of all the various enclosures and interconnected HVAC systems of a building or of one or more rooms in a building constitutes the "confinement system" for that building, room, or set of rooms or areas.

Three physical zones exist in the Fuel Fabrication Building:

1. restricted access — houses equipment containing SNM;
2. limited access — provides sampling and maintenance access to the restricted access zone;
3. normal access — operational controls and normal personnel flow zone.

The barriers of an enclosed zone are designated by classification of that zone; that is, restricted access zones are defined by restricted access barriers, limited access zones by limited access barriers, and normal access zones by normal access barriers. Pressure differentials, created and maintained by the HVAC system, exist between atmospheric air pressure through normal access to limited access to restricted access zones. The lowest pressure is in the restricted access zone so that leakage, if any, is always toward an area of higher contamination potential.

5.2 Ventilation Systems

The release and dispersal of plutonium materials are the principal risks of plutonium fuel fabrication plants. The ventilation systems of plutonium fuel fabrication plants ensure the confinement of plutonium materials during normal and abnormal conditions. The system consists of fresh air supply, process ventilation and exhaust air systems, together with associated air heating units, filters, fans, dampers, ducts, fire-fighting devices, control instrumentation, and regulation devices. The air supply system draws in and conditions fresh air and distributes it throughout the plant. A portion of supply air enters the process ventilation system through process enclosures and other components and is removed together with other plant air through the exhaust ventilation system. The exhausted air is filtered through fire-resistant Hepa filters and discharged through a stack which allows prompt, adequate dispersion in the event of accident conditions.

The ventilation systems serve as principal confinement barriers in the multiple confinement barrier system. These systems maintain pressure differentials between building confinement zones and also between the building confinement zones and the outside atmosphere; hence, airflow is from zones of lesser potential for contamination to zones of greater potential for contamination (see Fig. 5.1).

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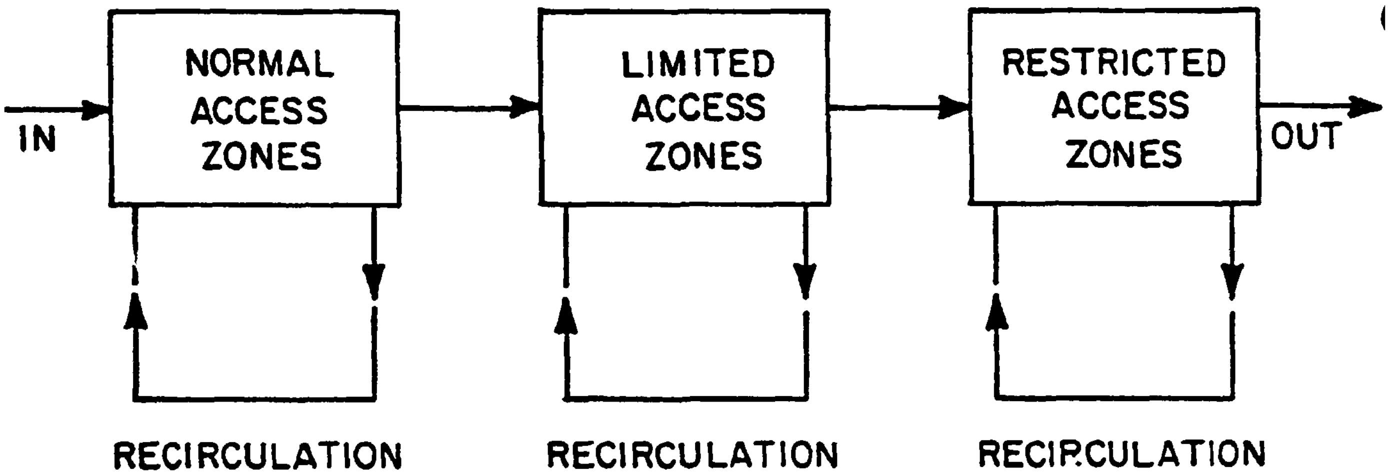

Fig. 5.1 Schematic Diagram of Fuel Fabrication Building Airflow.

6. SAFETY AND PROTECTION MEASURES

6.1 Protection Against Criticality

In radioactively hot facilities, the safety relating to criticality depends on prevention, detection, and personnel evacuation. Each of these three steps is discussed below.

6.1.1 Prevention

The prevention of criticality accidents is based on critically safe equipment and/or critically safe storage. Critically safe equipment is defined as equipment designed with dimensions or materials such that criticality accidents could never occur. Critically safe storage is defined as an area in which the quantities of fissile materials are limited to well-defined safe amounts.

The dimensions of critically safe equipment, as well as the authorized amounts of fissile materials in critically safe storage, result from criticality calculations based on criteria and operating conditions that have been accepted by the nuclear industry and from safety coefficients.

6.1.2 Detection and alarm

Detection and alarm systems are provided wherever there is a risk of accidental criticality. The criticality detectors are designed so that the criticality accident is detected with a very short time delay. Gamma-ray detection can be used uniformly throughout the system. To avoid false alarms, the detection and alarm system provides reliable single detector channels and/or concurrent response of two detectors minimum.

6.1.3 Evacuation

If a criticality accident occurs, all the employees inside the plant have to be evacuated. Alarm units are installed at any place where an individual may be present whose immediate, rapid, and complete evacuation is essential. The plutonium process buildings are designed so that within a well-defined time delay, any individual can leave the building where the accident occurred. The total thickness of the walls separating the process areas will reduce the radiation doses received by most of the operating personnel.

6.2 Dosimetry

The Gel-Sphere-Pac LWR plutonium Fuel Refabrication Plant is designed, constructed, tested, and operated under rigid quality assurance programs to ensure that operating people are not exposed to internal and external radiation which exceed current regulations in the U.S.A. This means that the radiation levels in all accessible areas are maintained below such criteria. Plant design and plant monitoring methods are utilized to ensure that these criteria are met. These methods are discussed below.

6.2.1 Plant design

To avoid any spread of activity (either alpha for plutonium or gamma for spiked fuel), the plutonium handling operations are carried out inside equipment that is located within process enclosures and maintained at a negative pressure relative to the adjacent areas of the process building. Furthermore, any suspected or slightly contaminated materials are treated or controlled in ventilated hoods. Outside the process enclosures, the plutonium-bearing materials or liquids are stored and/or transferred according to well-defined procedures using leaktight devices. The individual protection of the operating personnel in the process areas mainly consists of special clothes, overshoes and masks, where required.

The radiation exposure of the operating personnel to gamma and neutron irradiations is limited by the use of biological shieldings and remote operating design for the coprocessed fuel fabrication plant. For the coprocessed-spiked plant the above applies, but a remote maintenance design must also be added.

6.2.2 Plant monitoring

Alpha contamination. The surface contamination monitoring consists of routine checks or special checks in the event of an incident. These routine and special checks are made using appropriate detectors such as alpha-scintillation counters and measuring either the surfaces or smears obtained with appropriate materials.

In zones occupied or to be occupied by workers, the atmospheric contamination is continuously monitored and compared with the applicable control level to ensure that workers are not exposed to concentrations exceeding those considered safe.

6.3 Safety and Licensability

Facilities for the refabrication of plutonium LWR recycle fuel must meet regulatory requirements for the protection of operating personnel and the general public. Current regulations in the U.S.A. governing fuel processing and fabrication facilities require that the radiation dose at the site boundary due to releases from the facility be effectively less than the dose due to background radiation.

All structures, systems, and components whose failure might result in doses which exceed the specified limits at the plant boundary must be designated as "important to safety" of operating personnel or analyzed for possible failure modes and effects. All structures, systems, and important-to-safety structures, systems, and components constitute the primary containment of radioactive materials. Secondary containment will include limited or no-access areas and controlled-ventilation areas. Access will be restricted by a combination of physical barriers and security measures. All structures, systems, and components important to safety will be designed to withstand the effects of natural phenomena likely to occur at the specific facility site. Redundant and/or diversion emergency backup systems will maintain uninterrupted operation of all systems related to containment of radioactive materials. Special nuclear materials will use geometry-controlled, concentration, or administrative control to prevent criticality. Potentially combustible or explosive materials will be specially handled to prevent incidents that might result in radioactive release. Potentially volatile or leachable waste materials will receive special treatment and fixation.

The principal difference between a plant fabricating spiked vs nonspiked $(U,Pu)O_2$ fuel is that the shielding must be increased for fuel process and storage areas in order to protect operating personnel. Also, as mentioned before, the plant is designed for remote rather than contact maintenance.

6.4 Environmental Assessment

In order to be licensed, fabrication facilities for plutonium recycle fuel must meet the same regulatory requirements as LWR reprocessing plants to ensure that the environment will be protected.

The design of the fuel fabrication facility must adhere to the concept of no releases of radioactive liquids to the environment. Aqueous solutions containing plutonium will be treated for plutonium recovery, concentrated, and solidified. Noncondensibles will be filtered and released as a gas.

Plutonium-containing solids are treated for plutonium recovery, converted to a nonleachable form, transferred to stainless steel containers, and stored in a stable geological formation. Solids that contain small amounts of beta and gamma activity are buried at licensed sites. Radioactive and noxious gases are thoroughly cleaned before release.

In summary, a Gel-Sphere-Pac LWR recycle plutonium fuel fabrication plant contains much less activity and generates much less liquid waste than a Purex LWR fuel reprocessing plant. It should produce less solid and liquid waste than a pellet-based LWR recycle plutonium fuel fabrication plant. It poses no new or unknown activity, or solid or liquid waste problems. Therefore, it should not pose any new environmental problems.

6.5 Building Safety

In plutonium fuel fabrication plants, the main risk to health and safety is the release and dispersal of plutonium materials caused by a fire or explosion. In the reference plant, the fire protection system is designed to prevent, detect, extinguish, limit, and control fires and explosions and their concomitant hazards and damaging effects.

6.5.1 Prevention

Plant area. The plant area is sufficiently isolated from the surroundings to limit any damage resulting from a fire originating outside the area. On the plant site, sufficient large physical barriers surrounding the buildings are built to avoid any transmission of a fire occurring in the environs.

Building construction. In general, heat-resistant and noncombustible materials are used practically throughout the reference plant, particularly in the plutonium process areas and in places essential for the functioning of confinement barriers and systems, for controlling radioactive materials, and for maintenance of safety control functions.

The structural shells, their supporting members, and the penetrations in these shells surrounding any area where plutonium is handled and where it could be accidentally dispersed are designed so that they will remain standing and continue to act as a confinement structure during a well-defined time delay in case of failure of the fire suppression system.

Buildings are separated from each other by open areas. When separate buildings have to be interconnected, long corridors equipped with fire-resistant doors on each end are built.

Isolation of process enclosures. The plutonium materials are processed through interconnected enclosures which are located in several plutonium areas, as described earlier in Sect 4. To avoid fire transmission to adjacent process areas, the process enclosures located in the intermediate walls of the room are equipped with fireproof locks which are open to allow material transfers. Special process enclosures that present high contamination and/or fire risks are operated under inert atmospheric conditions.

Gas-handling equipment and flammable materials. Flammable materials are not introduced in buildings where plutonium is processed, except when specifically required for process reasons. The hydrogen required in the process is stored in tanks located outside the buildings. The hydrogen is diluted to a nonflammable percentage with inert gas prior to its introduction in the process building.

Solvents and other flammable liquids, besides the small quantities in use, are stored in a separate building or in an unexposed storage area. Special control is exercised over the handling of flammable, toxic, and explosive gases, chemicals, and materials admitted to the plutonium-handling areas and process enclosures.

Exhaust filter protection. The medium-efficiency room exhaust filters are protected by a spark-arrestor flame trap and a fire-resisting prefilter. The medium-efficiency filters and the Hepa filters installed in the plutonium process building and process enclosures ventilation systems withstand high temperatures during well-defined time delay without any loss of efficiency.

6.5.2 Fire detection and alarm systems

Provisions have been made for fire detection and alarm systems that consist of fire detectors, signaling devices, and audible and visual indicators in a constantly attended location, as well as in other appropriate plant locations.

The types of fire detectors are chosen as a function of the possible types of fires. The fire detectors are connected to plant-wide fire detection, signal, and alarm systems that can detect and clearly locate the fire within 1 min.

Manual fire alarm stations, connected to the plant-wide fire detection systems, are installed throughout the plant at immediately accessible places.

6.5.3 Fire suppression agent and techniques

Different fire-fighting techniques, products, and equipments are used in plutonium fuel fabrication plants, depending on the type, size, and the hazard of the fire which could break out.

Fire hydrants or connection points for hydrants are strategically located around a water distribution loop encircling the buildings site; hence, it is possible to spray all points of the plant area. Wet-pipe conventional automatic sprinklers are used in nonprocess areas of the facility.

For process areas, if automatic water sprinkler coverage is used, the sprinkler system selected minimizes the quantity of water used, the spread of contamination by water, and the possibility of criticality. Process areas not protected by automatic water sprinklers are protected by some other fire suppression agents such as carbon dioxide, high expansion foam, etc.

An automatic fire-extinguishing system is provided in the process enclosures wherein work entailing a serious risk for fire is carried out. Depending on the plutonium-bearing materials or liquids being treated inside the process enclosures, fire suppression agents such as high expansion foam or halogenated organic components are used.

As a supplementary caution, portable fire extinguishers filled with various fire suppression agents are distributed throughout the plutonium plant.

7. STATUS OF TECHNOLOGY

The status of the development of microsphere and Sphere-Pac technology is far behind pellet technology. The microsphere and sphere-pac concepts originated in the United States almost 20 years ago (as "sol-gel"), and active development was pursued in this country until 1972. At that time, the U.S. fast reactor program concentrated on pellet fuel, and support to Gel-Sphere-Pac technology at this time was thoroughly documented.[5,6-8] However, several foreign countries, including the Netherlands, the United Kingdom, Germany, and Switzerland have continued their microsphere fuel development and have made significant contributions. The U.S. Gel-Sphere-Pac work was reinitiated in June 1977.

The status of development for the two major Gel-Sphere-Pac areas (gel-sphere preparation and sphere-pac loading) is roughly the same. Gel-sphere preparation has received more attention for a longer period than sphere-pac loading, but it is significantly more complex. Therefore, their remaining overall development needs are estimated to be about equal.

A discussion of development status and needs is conveniently organized along two standards: the scale of operation and the various functional systems involved. For processes aimed eventually at the design, construction, and successful operation of a commercial facility that requires remote handling (shielded hot cell), the following sequence is both realistic and representative of the actual number of development stages needed:

1. Cold lab: to demonstrate process feasibility using low-activity stand-ins.
2. Hot lab: to verify process feasibility using highly gamma-active materials.

3. Cold engineering: to demonstrate equipment concepts under nonradioactive conditions.
4. Hot engineering: to verify equipment concepts under remote, high gamma activity conditions.
5. Cold prototype: to demonstrate full-scale components, including integrated and/or remote operation for the more complex steps.

In general, cold-lab work provides the basis for both hot-lab and cold-engineering work. The latter two together provide the basis for both hot-engineering and cold-prototype work, which in turn provide a solid basis for a commercial-scale facility. Fuel samples for irradiation testing would normally be produced during all stages of development. In the above sequence, sphere-pac development is well into cold lab. Work is beginning on both hot lab and cold engineering.

Some irradiation testing has been done, both in the United States and in Europe, with test pins of various lengths, with generally favorable results; additional tests are under way in Europe and in preparation in the United States.

From a functional viewpoint, sphere-pac development may be divided into the following areas: calcination and sintering, sphere characterization, fuel rod loading, fuel rod inspection, and scrap recycle.

Calcining and sintering are being done successfully on a batch basis, yielding product greater than 98% of theoretical density. However, considerable development is still required in order to understand and optimize these processes for the heavy-metal compositions of interest. Scale-up will require equipment for continuous operation and/or larger batches, while providing the necessary atmosphere control, residence time, and uniformity.

Considerable technology has been developed for microsphere characterization as part of the HTGR program.[9,10] Contact or glove-box techniques have been developed for the determination of particle density, size, shape, chemistry, crushing strength, and microstructure. However, a need still exists for techniques that can be applied to the fines and more rapid methods of chemical analysis.

The sphere-pac process for loading a fuel rod involves vibratory packing of carefully sized spheres of the proper size ratio. Considerable technology has been developed regarding the identification of proper sizes, size ratios, and blending ratios and loading sequences to produce maximum smear densities and minimum loading times. Sphere-pac loading of commercial-length rods remains to be demonstrated. Simultaneous loading of all three size fractions shows promise of overcoming the problem of excessive loading time for long rods. Much of the particle dispensing and blending technology developed for HTGR fuels is applicable.

Significant development is required to enable economic inspection of fuel rods with acceptable precision, accuracy, and speed, although most of the development is required for remote inspection, regardless of whether the fuel rod is fabricated from pellet or Gel-Sphere-Pac fuel.

Compared to pellets, scrap recycle in Gel-Sphere-Pac is a much smaller problem since microsphere dimensions are not as critical as pellet dimensions. Any defective microspheres can be recycled after drying, while dissolution is still relatively easy, before sintering to density.

Very little effort to date has been directed toward planning and analysis of an integrated commercial refabrication plant based on Gel-Sphere-Pac technology. Concepts for Gel-Sphere-Pac processes and equipment are rapidly progressing to the point where meaningful evaluation can and should be performed.

A thorough irradiation test program is needed since performance is the crucial item in the final acceptance of Gel-Sphere-Pac from both commercial and licensing aspects.

8. REFERENCES

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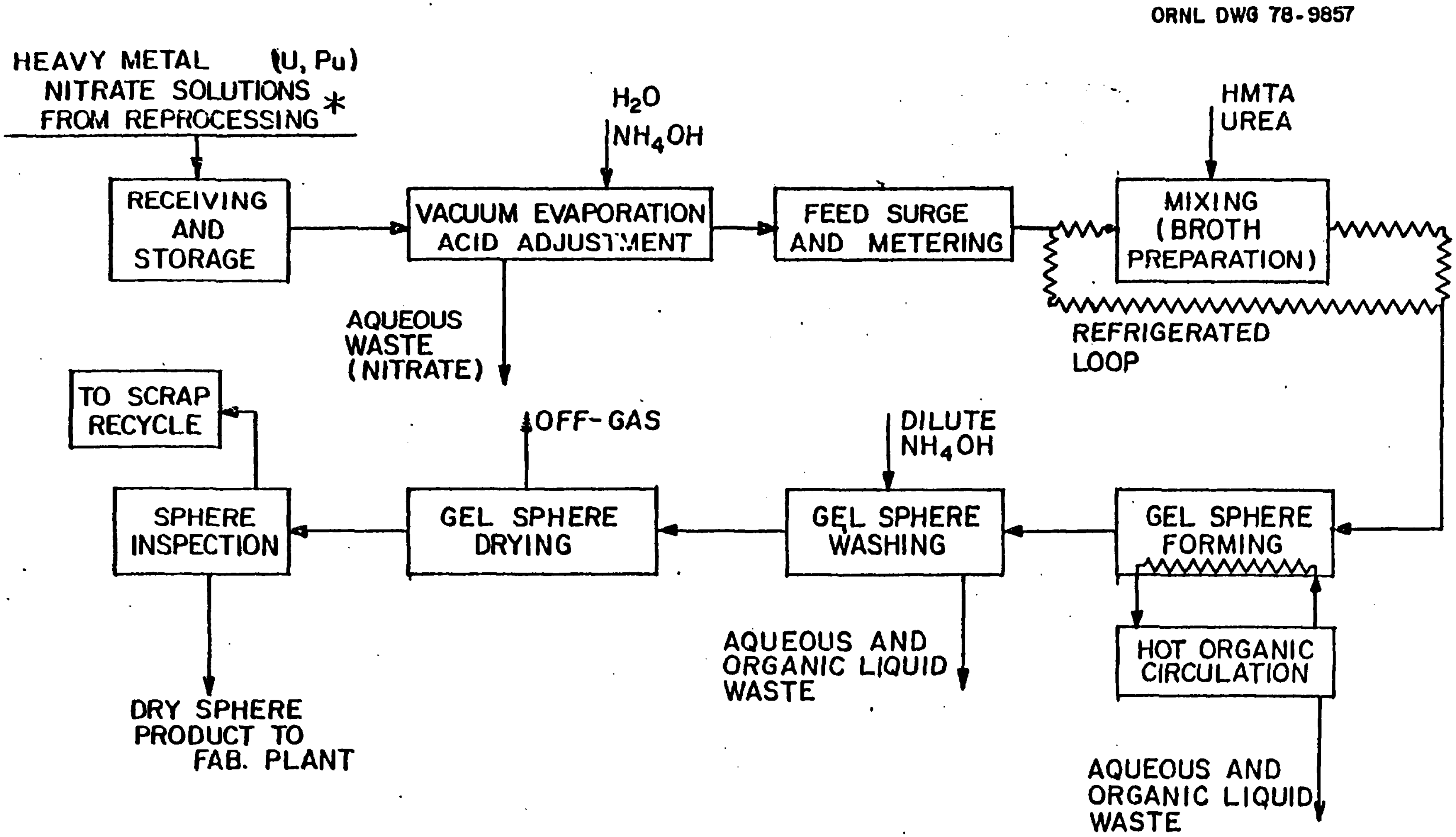
APPENDIX A: DESCRIPTION OF THE SPHERE-CONVERSION PROCESS

An alternative to conventional conversion processes is sphere-conversion which utilizes a gel-sphere process to prepare a free-flowing starting material made up of gel-spheres that are suitable for sintering to high density and direct loading into fuel pins using low-energy vibration. Loading microspheres directly into fuel pins using low-energy vibration is called the Gel-Sphere-Pac process.

A.1 Flowsheet and Process Description

Sphere conversion is based on three major steps: (1) preparation of a special solution ("broth"), (2) gelation of broth droplets to give semi-rigid spheres, and (3) washing and drying to give a dry gel-sphere product suitable for shipping to a fuel refabrication plant. Gelation is accomplished chemically by the use of ammonia which is formed within the broth droplet utilizing hexamethylenetetramine decomposition. This method is called internal gelation. Gelation may also be accomplished externally using ammonia gas and ammonium hydroxide. This method is called external gelation. Internal gelation is the process that has been selected for discussion in this report and is widely known throughout Europe as the KEMA process.[1] This process is currently being developed in the United States under the sponsorship of the DOE Fuel Refabrication and Development program at the Oak Ridge National Laboratory.[2]

A generic functional flow diagram for sphere conversion is shown in Fig. A.1. Note that various mixtures of uranium and plutonium can be prepared by adjustment of the heavy-metal feed material. Similarly by utilizing spiked feeds, highly radioactive fuel cycle options can be accommodated. The flowsheet in Fig. A.1, therefore, represents the preparation of mixed $(U,Pu)O_2$ fuel for both fabrication plants in this study. Although the flowsheets and discussions are intended to describe the preparation of larger gel spheres, they apply also to the preparation of fertile fines which are made in a contact facility.



* NOTE FOR LOW DF OR SPIKED VARIATIONS, THE HIGH LEVEL ACTIVITY IS ASSUMED TO BE INCLUDED IN THIS SOLUTION.

Fig. A.1 Generic Functional Flow Diagram for Gel-Sphere Preparation (Sphere-Conversion).

A.1.1 Receiving and storage

This process step provides the capacity for receiving and storing the end product of the liquid portion of reprocessing plant. In addition, the ability to mix heavy-metal nitrate solutions to the required composition must be provided. The involved operations include fluid transfer, storage, mixing, and analysis. Many of the requirements for this step are similar to those required earlier in the reprocessing cycle. Examples of these requirements are: (1) ensuring criticality safety in all operations, (2) verifying correctness of transfer contents, (3) use of on-line analysis or special facility design to safeguard transfers and instrumentation of the system so that any changes are instantly and accurately recorded and announced.

A.1.2 Vacuum evaporation and acid adjustment

This process step adjusts the heavy-metal feed solution to a usable concentration and acidity (free nitrate). A vacuum evaporator is used to minimize the temperature during concentration. Acidity adjustment (utilizing NH_4OH) is made to pre-neutralize the heavy-metal nitrate solution so that gelation during sphere formation will occur in the required time span.

A.1.3 Mixing (broth preparation)

The next major process step is broth preparation. This step requires the modification of a heavy-metal nitrate solution to a form that is suitable for forming gel-spheres; a "broth" is formed by adding organics such as urea and hexamethylenetetramine to the heavy-metal nitrate solution. Urea is added to complex the heavy-metal ions, and the amine provides an internal source of ammonia necessary for causing gelation of the broth droplets in a heated organic. The mixing of organics with heavy-metal nitrates must be accomplished at a reduced temperature (about 0°C) in order to prevent premature gelation. Therefore, this step requires a refrigerated loop.

A.1.4 Forming and washing of spheres

This operation requires forming spherical droplets of broth, gelation to form gel microspheres, and washing to remove urea, nitrates and amine prior to drying. Droplet formation is accomplished by a droplet generator. The process step must yield very high percentages of spherical product in a narrow-size range; therefore, a pulsed nozzle is generally used. The wash procedure must remove a majority of the organics and nitrates and give a product that is capable of sintering to high denisty and provide gel spheres that can be handled during drying and pneumatic transfer.

Droplets of broth are formed in a heated organic which causes both sphere formation and gelation. Gelation occurs as a result of the heated organic, thus causing amine decomposition to ammonia which directly causes broth gelation. Washing of the gel spheres is accomplished by the use of dilute ammonium hydroxide.

A.1.5 Drying of spheres

This step requires drying wet gel microspheres while maintaining them in an intact state. The dry product must be strong enough for pneumatic transfer formation and must be capable of sintering to high density (while remaining intact) for sphere-pac applications.

A.1.6 Sphere inspection

This process step is required to ensure that the required quality specifications for the dry gel-sphere product are met prior to shipment to the fuel fabrication plant. Reject material is recycled through the reprocessing plant scrap recovery system. Scrap recovery at this point in the system should be relatively easy since only dried (and not sintered) material is being rejected.

The inspections to be performed would include the following: impurities, sphericity, size distribution, and composition (fissile content). Development needs include faster techniques for size, size distribution, and sphericity (particularly with respect to fine fertile microspheres made in contact facilities).

A.2 Status of Technology

The status of gel-sphere technology was discussed in Sect. 7 of this report along with sphere-pac loading technology.

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