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A Review of Solid Radioactive Waste Practices in Light-Water-Cooled Nuclear Reactor Power Plants

A. H. Kibbey
H. W. Godbee
E. L. Compere

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Safeguards, Fuel Cycle and Environmental Research
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ABSTRACT

This survey was made to update the report published by Oak Ridge National Laboratory in 1974 which reviewed solid radioactive waste (radwaste) practices at light-water-cooled nuclear reactor (LWR) power plants. The main source of information in both surveys was docket material including plant annual operating reports, semiannual effluent release and waste disposal reports, etc. The earlier study covered initial criticality to December 31, 1972, while this study covers initial criticality to December 31, 1977.

A comparison of pressurized water reactors (PWRs) and boiling water reactors (BWRs) shows that BWRs consistently shipped a larger total volume of solid radwaste per thermal megawatt-hour than PWRs. At the end of 1977, the cumulative thermal megawatt-hour output was 1.8×10^9 for PWRs and 1.2×10^9 for BWRs included in this survey. The corresponding cumulative volume of solid radwaste shipped from PWRs was approximately 5.6×10^4 m^3 and from BWRs was 7.7×10^4 m^3, or 3.1×10^{-5} and 6.4×10^{-5} m^3/MWhr(t) for PWRs and BWRs respectively. The cumulative total curie (uncorrected for decay) contents of these wastes were 5.8×10^4 Ci for the PWRs and 1.2×10^5 Ci for the BWRs, which give average specific activities of 1.0 and 1.6 Ci/m^3 for the PWR and BWR wastes respectively. Through the end of 1977, the average number of curies shipped offsite to licensed burial grounds per unit of thermal output is about 3.2×10^{-5} Ci/MWhr(t) for PWRs and 1.0×10^{-4} Ci/MWhr(t) for BWRs. Shipments per 10^6 MWhr(t) averaged about 2 for PWRs and about 9 for BWRs.

Cement (or cement plus silicate) and urea-formaldehyde resins are the main agents used to solidify radwaste solutions and slurries at LWRs for offsite shipment. However, the use of asphalt and modified vinyl ester resins (or water-extensible polyester) as solidification agents appears near. Among the problem areas reported in radwaste solidification at LWRs were: drum capping, which remains largely a manual operation; poor performance of sonic level indicators, which are noisy and unreliable; oil contamination in the liquid waste streams, which can interfere with the solidification process in some cases (e.g., cement); and free liquid in containers of solidified wastes (especially with the urea-formaldehyde resins).

1. SUMMARY AND RECOMMENDATIONS

The relationships between solid radioactive waste (radwaste) volume, curie content, and size and number of shipments were studied. These radwaste variables were normalized on the basis of thermal megawatt-hours. All operating light-water-cooled nuclear reactor (LWR) power plants in the United States, starting with Dresden Unit 1, were considered from first criticality through December 31, 1977. The main source of information was docket material such as plant annual operating reports, semiannual effluent release and waste disposal reports, etc. In addition, all operating plants were sent questionnaires on their solid radwaste handling procedures. Data on waste core components and structurals shipped offsite, although compiled and included in an appendix, were excluded from the analysis of data because this study was concerned mainly with the trends of routine solid radwaste generated from operation of systems used to treat radioactive liquids. The routine wastes considered in this study are filter cartridges and sludges, spent ion-exchange resins, evaporator concentrates, and dry compressible wastes which are shipped for offsite burial. In the overall analysis, these are grouped together and referred to as total solid radwaste shipped.

Comparison of boiling water reactors (BWRs) and pressurized water reactors (PWRs) indicates that BWRs generate a larger volume of solid radwaste per thermal megawatt-hour than PWRs and that the curies (uncorrected for decay) shipped per thermal megawatt-hour is about three times greater for BWRs than PWRs. At the end of 1977, the cumulative thermal megawatt-hour output was 1.8×10^9 for PWRs and 1.2×10^9 for BWRs included in this survey. The corresponding cumulative volume of solid radwaste shipped from PWRs was approximately 5.6×10^4 m^3 and from BWRs was about 7.7×10^4 m^3. The cumulative total curie contents of these wastes were 5.8×10^4 Ci for PWRs and 1.2×10^5 Ci for BWRs. From 1960 through 1977, BWRs made more than four times as many shipments as PWRs per thermal megawatt-hour, with an average BWR shipment equivalent to about 7.4 m^3 as compared to about 15 m^3 for PWRs. Thus, in recent years, the tendency has been for PWRs to make fewer shipments of larger volume and lower specific activity (Ci/m^3) waste per thermal megawatt-hour than BWRs. For each year since 1967, the normalized annual BWR solid radwaste volume has been a factor of two to six greater than that for the PWRs. In-depth studies that consider basic differences in the waste management philosophy of the nuclear-steam-supply system (NSSS) vendors, architect-engineers, and utility companies are needed before more definitive evaluations can be made.

The practice of merely dewatering spent ion-exchange resins and packaging them in disposable cask liners or drums without a binder is widespread among both types of plant. All PWRs, except San Onofre, Kewaunee, and St. Lucie, use evaporators on their miscellaneous wastes. The concentrates from the waste and boric acid recycle evaporators at PWRs are incorporated in a solidification agent. The PWRs which have solidification equipment may also incorporate their disposable filter cartridges and sludges in the solid. A number of BWRs do not have evaporators and instead use a maximum-recycle filter/demineralizer system with no resin regeneration. These plants produce relatively large amounts of sludge, which they dewater and package in the same way as they treat bead resins. In plants that have no evaporator and inadequate solidification equipment, chemical wastes have sometimes been adsorbed on such materials as vermiculite or Micro-Cel in disposable cask liners or drums and shipped for offsite burial [illegible] a binder. There has been a recent trend away from these [illegible] and many BWR plants have now installed waste evaporators and [illegible] for incorporating sludges in a solid matrix. Many PWRs and [illegible] solidification equipment have experienced the problem of [illegible] (i.e., liquid associated with the solidified waste that is neither [illegible] nor physically bound by the solid matrix). At present, process control within certain parameter limits is probably the best method available to ensure that there is no free liquid. Studies are required on the effect that organics (e.g., antifoam agents in evaporator concentrates) have on solidification processes. More information on the leach rates of fission products (especially cesium) from solidified products is needed as well as greater knowledge of their physical and chemical properties under conditions of long-term storage. Another recognized need is a more precise definition of "solid" which sets acceptable limits on the basis of physical and chemical properties such as compressive strength, flammability, chemical inertness, and the ease with which it is dispersed by the natural forces of wind, rain, and groundwater.

The requisite cleanup of radioactive streams at LWRs is obtained by the combination of a number of physical and chemical separations processes. The processes most frequently used are evaporation, which leads to concentrates; filtration, which leads to sludges; and ion exchange, which leads to spent resins. *The amounts of these evaporator concentrates, filter sludges, and spent resins shipped from LWR plants should each be reported separately in the dockets so that more meaningful evaluations of the overall effectiveness of these separations processes can be made. Also, the curie contents corrected for decay before shipment would allow for more meaningful comparisons.*

2. BACKGROUND

The purpose of this review was to evaluate solid radioactive waste (radwaste) practices in light-water-cooled nuclear reactor (LWR) power plants in the United States. This compilation of available information on solid radwastes generated at the various plants includes: volume and curie content of the wastes, solidification and packaging methods used, and size and number of shipments made through December 1977. The results of this study provide operating data to assist the Nuclear Regulatory Commission (NRC) in its evaluation of solid radwaste management systems used in nuclear power plants. In a broader sense, they should prove useful to all facets of the nuclear power industry for appraising and improving the management of solid radwastes. This study constitutes an updating of the one[1] published by Oak Ridge National Laboratory (ORNL) in 1974. Other similar surveys that touch on solid radwaste practices at nuclear power plants are included in refs. 2-11.

Operating nuclear power plants generate various types of solid, liquid, and gaseous wastes containing radioactive materials. The quantity of these wastes varies between plants and is frequently different between pressurized water reactor (PWR) and boiling water reactor (BWR) plants of comparable size. Of the three forms of waste mentioned, only solid radwastes are considered in this study. As more plants move toward reducing the volume of liquids discharged and/or decontaminating liquids to a higher degree before discharging them, the quantity of solid radwaste generated increases.

Solid radwastes have been classified[12] as "wet" or "dry." Wet wastes consist mainly of spent bead and powdered resins from ion-exchange units, sludges from filters and resin-cleaning operations, and concentrates from evaporators and reverse-osmosis units. These derive largely from water treatment or purification of several liquid streams in the nuclear plant. Spent filter cartridges are also wet wastes which usually require shielding because of their high radiation levels. The bulk of dry waste consists of ventilation air filters and contaminated clothing, rags, and papers which are normally of low enough radiation level to permit contact collection and manual packaging for offsite shipment.

Additionally, plants may generate small amounts of highly radioactive dry wastes such as control rod blades, fuel channels, in-core instrumentation, and other reactor vessel components. These wastes must be processed individually with special decontamination and packaging, and since they are not handled in the routine waste collection and packaging systems considered here, they are placed in a special category.

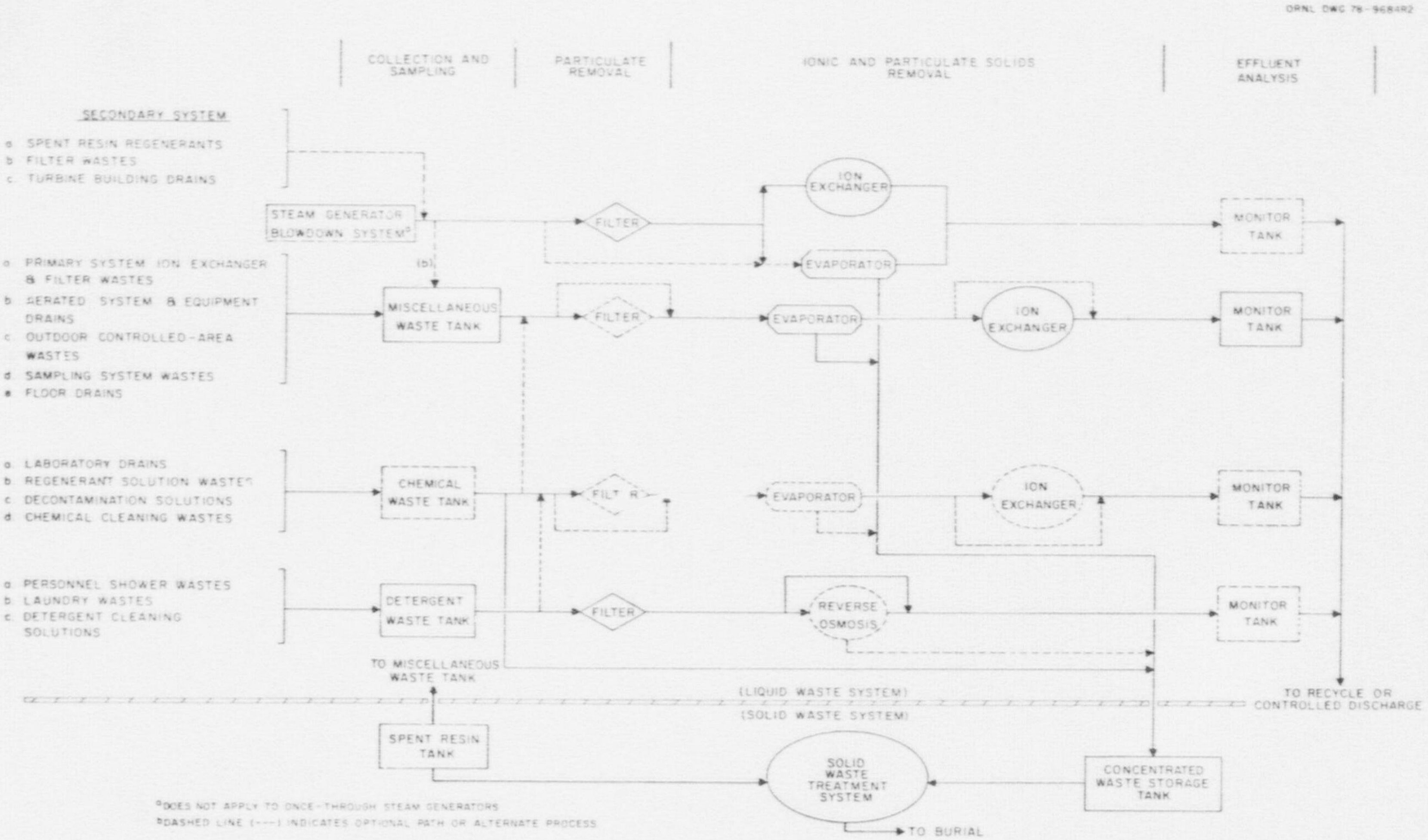
The bulk of the data in this study was taken from docket material such as annual operating reports, semiannual effluent release and waste disposal reports, etc. In addition, as a part of this study, a number of installations were contacted to obtain performance data on radwaste management practices at PWR and BWR plants. They include 44 operating nuclear power plants or stations (representing 37 PWRs and 25 BWRs), 31 plants under construction (representing 51 PWRs and 21 BWRs), 13 suppliers of radwaste treatment equipment and/or services, 4 nuclear-steam-supply system (NSSS) vendors, and 12 architect-engineers.

A characterization of streams normally treated which give rise to solid radwaste at LWR plants is presented in the next section.

3. TYPES OF STREAMS TREATED

In LWR nuclear power plants, the liquid streams have various amounts of dissolved plus suspended solids and varying amounts of radioactivity associated with them, depending upon their source within the plant. Corrosion products in the coolant stream become activated in the internals of the reactor core, producing such radioactive species as ^{58}Co, ^{60}Co, ^{54}Mn, ^{51}Cr, ^{58}Ni, and ^{59}Fe. Defective fuel and uranium present on the cladding of fuel elements (tramp uranium) also contribute radioactive fission products such as ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{131}I, and ^{85}Kr. Generally speaking, relatively significant fractions (i.e., about one-fourth)[13] of the activated corrosion products (especially iron and nickel) tend to be present as suspended solids,[13-15] and fission products tend to be present dominantly as soluble forms. The facilities and equipment to collect and process radioactive liquid streams enable the nuclear industry to hold releases of radioactive material in liquid effluents within applicable regulatory limits. These limits are most readily met by minimizing the volume of liquids discharged and/or by decontaminating the liquids to a high degree before discharging them. The requisite cleanup of radioactive liquids at LWRs is obtained by the combination of a number of physical and chemical separations processes or unit operations. Presently, the unit operations used most frequently are evaporation, filtration, and ion exchange. Used to a lesser extent are centrifugation and reverse osmosis. Typical use of these operations in the liquid radwaste system for a PWR plant[16] is illustrated in Fig. 1 and for a BWR plant[17] in Fig. 2. The use of ion exchange, filtration, and evaporation to treat other liquid streams are described in refs. 18, 19, and 20 respectively.

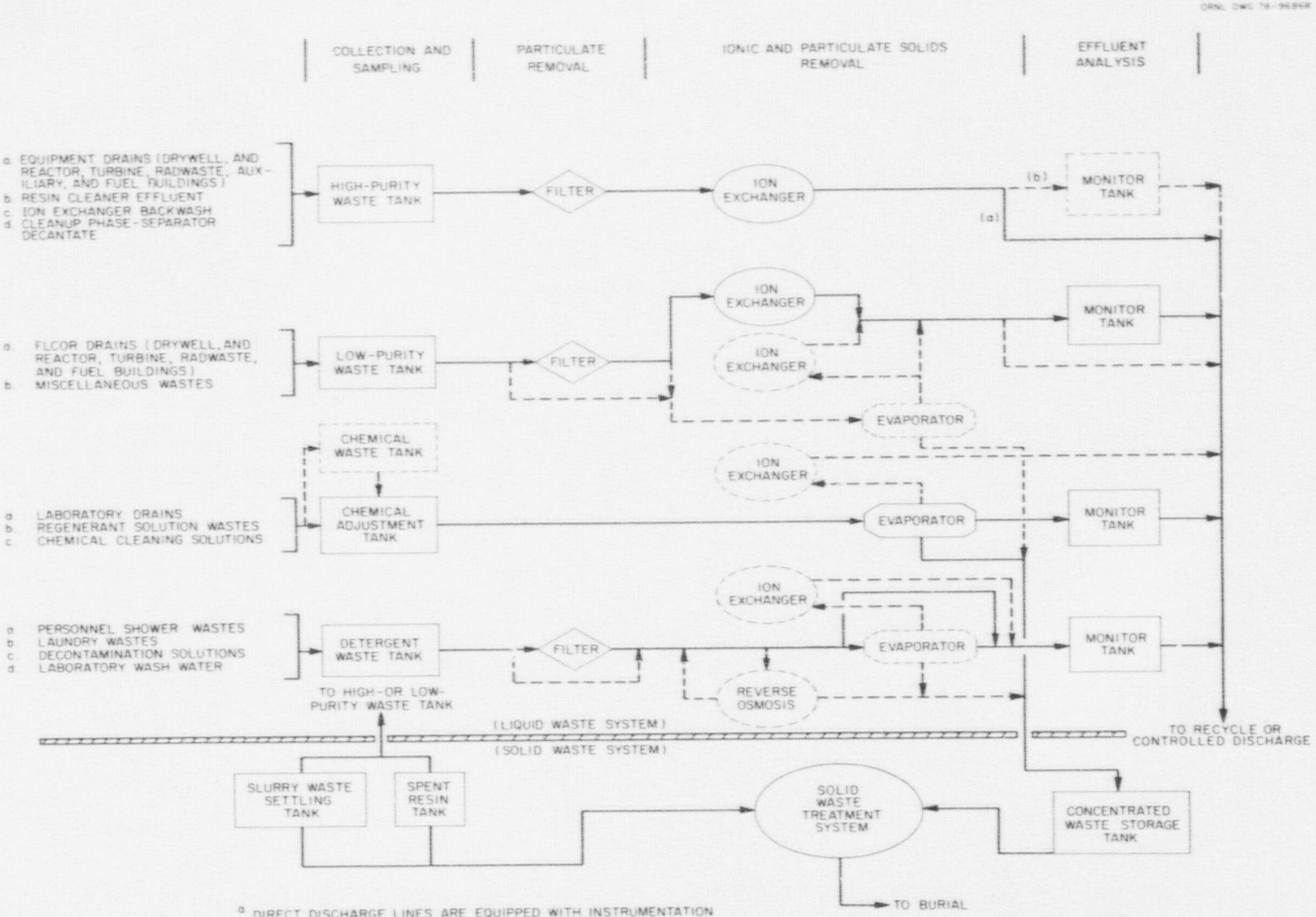
Many nuclear power plants are moving toward a concept of "maximum recycle" (of water) or near "zero release" (of radioactivity) for radioactive liquids as alluded to above. Either of these modes of operation necessarily results in an increased volume of solid radwaste to be shipped offsite for burial. Although many of the early nuclear plants still ship solid wastes in the form of dewatered sludges and resins (powdered or bead) or evaporator concentrates immobilized (see Sect. 10



[a] DOES NOT APPLY TO ONCE-THROUGH STEAM GENERATORS

[b] DASHED LINE (---) INDICATES OPTIONAL PATH OR ALTERNATE PROCESS

Fig. 1. Flow diagram of a basic liquid radioactive waste processing system for a PWR. (Adapted from a similar drawing in American National Standard N199-1976/ANS-55.2)



[a] DIRECT DISCHARGE LINES ARE EQUIPPED WITH INSTRUMENTATION TO ASSURE THAT WATER QUALITY LIMITS ARE MET.

[b] DASHED LINE (———) INDICATES OPTIONAL PATH OR ALTERNATE PROCESS.

Fig. 2. Flow diagram of a basic liquid radioactive waste processing system for a BWR. (Adapted from a similar drawing in American National Standard N197-1976/ANS-55.3)

for definition of terms) by entrapment on sorbent materials, some of these older plants are now being, or have been, serviced by mobile solidification units. All new plants now being licensed are required to have permanently installed solidification systems.

3.1 Pressurized Water Reactors (PWRs)

The bead resins commonly used for coolant purification at PWR plants are seldom regenerated but instead are replaced. The spent resin slurry, when prepared for solidification, normally contains from 35 to 50 wt % water, depending upon the solidification agent to be used. More liquid is required for solidification in cement than for solidification in an organic matrix. Typically, these resin slurries are neutral with respect to acidity, and as feed to a solidification process, they are near ambient temperature.

A survey[21-26] by Brookhaven National Laboratory (BNL) of wastes commonly solidified at LWRs indicated that a PWR resin regenerant solution when concentrated in a present-day forced-circulation evaporator typically would contain, on a weight basis, nearly 15% sodium sulfate, approximately 9.6% ammonium sulfate, about 2% sodium chloride, and 0.1% undissolved solids (crud). If solidified immediately after discharge from the evaporator, the temperature would be around 170°F, and the pH would be in the range of 2.5 to 4.0.

The boric acid waste from a PWR, if similarly treated, typically would contain 12 wt % boric acid at pH 3.5. The amount of undissolved solids would again be about 0.1 wt %.

The waste generated in decontamination of a forced-circulation evaporator could contain, on a weight basis, about 80% water, 5% each citric acid and ethylene diamine tetraacetic acid (EDTA), 0.4% oils, 9.4% cleaning compound(s), and 0.2% crud. The pH would be about 3.5.

3.2 Boiling Water Reactors (BWRs)

For comparison purposes, BWRs were categorized as deep-bed or filter/demineralizer. Each generates different types of wastes. The representative wastes from each type, based on the BNL survey (refs. 21-26), are described in the following sections.

3.2.1 Deep-bed plants

Most BWRs that mainly use deep beds of ion-exchange bead resins for stream cleanup do regenerate these resins. At discard, these resin slurry wastes are similar to those described in the previous section for PWRs. However, the expected regenerant solution waste when concentrated in a present-day forced-circulation evaporator would be slightly different from that expected in PWR resin regeneration. It would contain no ammonium sulfate, and the total salt concentration on the basis of weight would be somewhat lower (i.e., 22.9% sodium sulfate plus the 2% sodium chloride). The crud level and temperature would be the same as for PWRs, but the pH would be higher (about 6). The decontamination solution waste from a BWR forced-circulation evaporator should be essentially the same as for one at a PWR.

The large volumes of sodium sulfate wastes generated at deep-bed BWRs make further concentration by a thin-film evaporator appear attractive.[27-29] The waste concentrate from a thin-film unit could contain only 50 wt % water, and the solids content could be about double that obtained with a forced-circulation evaporator. The pH would not change, but the discharge temperature would range between 150 and 250°F.

When deep-bed BWRs use pressure precoat filters for in-plant stream cleanup, they frequently use powdered resins and diatomaceous earth (or mixtures of the two) as precoat materials. When powdered resin is used alone, the filter sludge wastes normally contain equal parts of powdered anion and cation resins. A resin slurry waste of this type is made up of roughly 50 wt % water, 40 wt % mixed resins, and 5 wt % each sodium chloride and undissolved material. The slurry pH is about 7, and handling is usually done at ambient temperature. By dewatering (sometimes with a centrifuge or flat-bed filter) to a water content of approximately 32 wt %, the mixed resin concentration is increased to 60 wt %, while the sodium chloride is reduced to 2 wt %. The amount of crud increases only slightly to ∼6 wt %, and the pH remains the same.

When diatomaceous earth (DE) is used as filter precoat in BWR inplant stream cleanup, the waste slurry produced is typically 75 wt % water, 20 wt % DE, and about 5 wt % other undissolved solids. The slurry is neutral pH, and generally it is treated at ambient temperature. A dewatered sludge would contain much more liquid than a dewatered resin, its water content being around 60 wt %. The total solids, including 10 wt % crud, etc., would make up the remainder. The dewatering methods used on resins at operating BWRs would not change the pH or the temperature.

3.2.2 Filter/demineralizer plants

The characteristics of the wastes generated at BWR plants that dominantly use filter/demineralizers for stream cleanup differ from deep-bed BWR wastes in that they do not regenerate the powdered ion-exchange resins; therefore, they have no regenerant solution wastes, that is, no sodium sulfate to solidify. They do have much larger volumes of powdered resin wastes to handle, but the physiochemical aspects of the solidification processes would be roughly the same as those for the powdered resin sludges generated at deep-bed plants.

4. ANALYSIS OF SOLID RADWASTE OPERATING DATA

Light-water-cooled nuclear reactor power plants licensed for operation as of December 31, 1977 (excluding Shippingport) were considered in this survey. The main source of information presented in this section is docket material such as plant annual operating reports, semiannual effluent release and waste disposal reports, etc. The results from the ORNL questionnaire on radwaste management practices are summarized in Sect. 7 and Appendix A. The docket information collected on radwaste volume, curie content, and number of shipments is tabulated in chronological order of initial criticality in Tables B-(1-28) in Appendix B for PWRs and in Tables B-(29-46) in Appendix B for BWRs. The docket information gathered on waste core components and structurals shipped from PWRs and BWRs is listed in Table B-47 in Appendix B. These docket data (excluding core components and structurals) are analyzed in the following sections.

4.1 Thermal Energy Output

Thermal output is one basis for comparing nuclear reactor waste generation, and it is used in this review as the common denominator for comparisons of practices in the management of solid radwaste at PWRs and BWRs. Thus, the annual outputs,[1,30-34] as thermal megawatt-hours [MWhr(t)], for both types of reactor as a function of time are given in Fig. 3. This plot shows that from 1967 to 1969, the PWRs had a higher annual total thermal output than the BWRs, which is a reflection of the larger PWRs [$\geq$1000 MW(t)] starting to operate. In 1970, the year after the first larger BWRs [$\geq$1000 MW(t)] began operation, annual BWR thermal output approximately equaled that of the PWRs. In the year 1972, the BWR thermal output slightly exceeded that for the PWRs. In 1974, the PWR output slightly exceeded that for the BWRs. In 1975-77 the PWR output has been almost twice that of the BWRs. This is presented only as background material and not as an attempt to estimate future nuclear power trends. To use the thermal output data for correlation purposes, cumulative totals were calculated as a function of time. In Fig. 4, a

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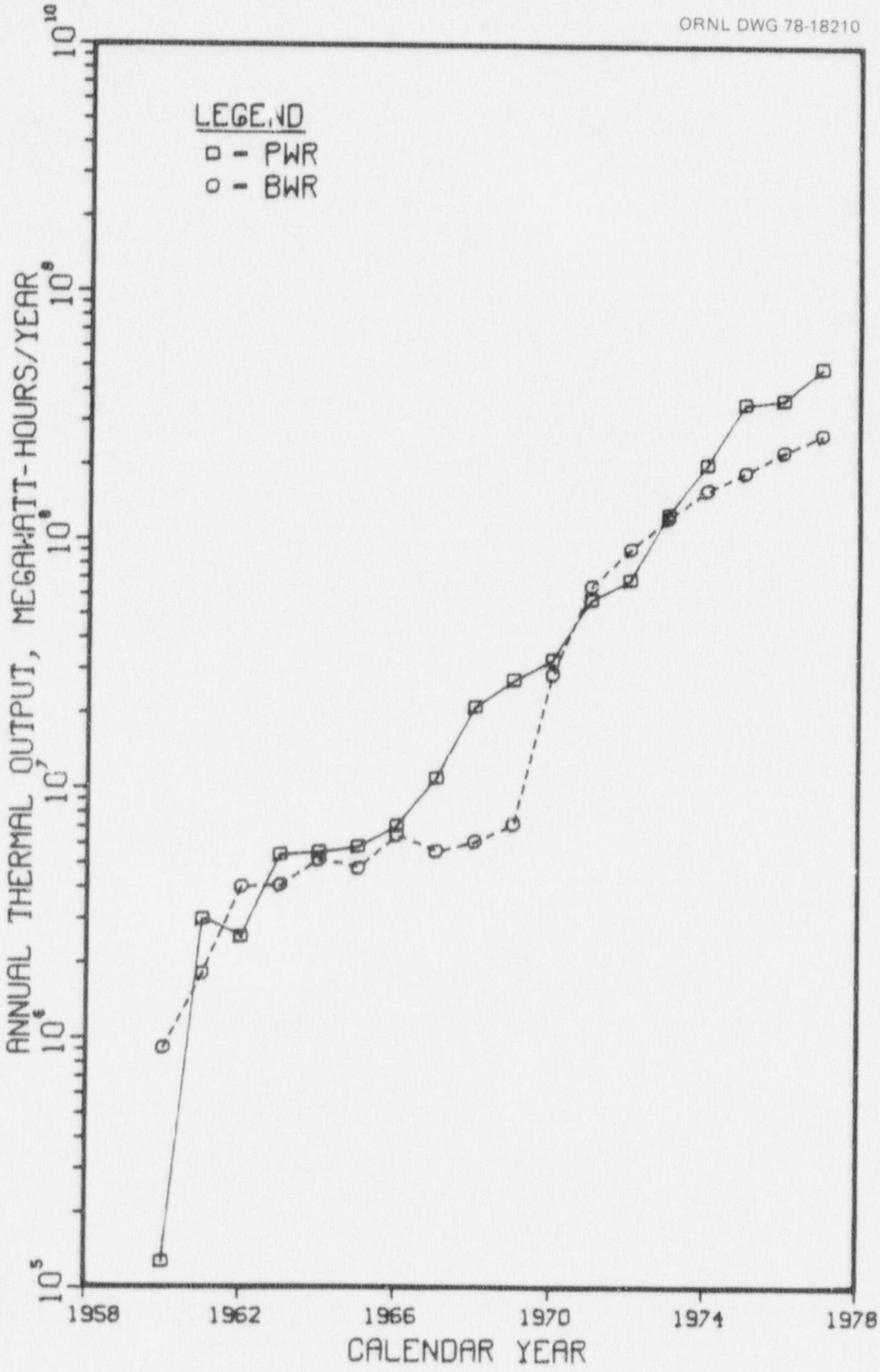

Fig. 3. Annual thermal output.

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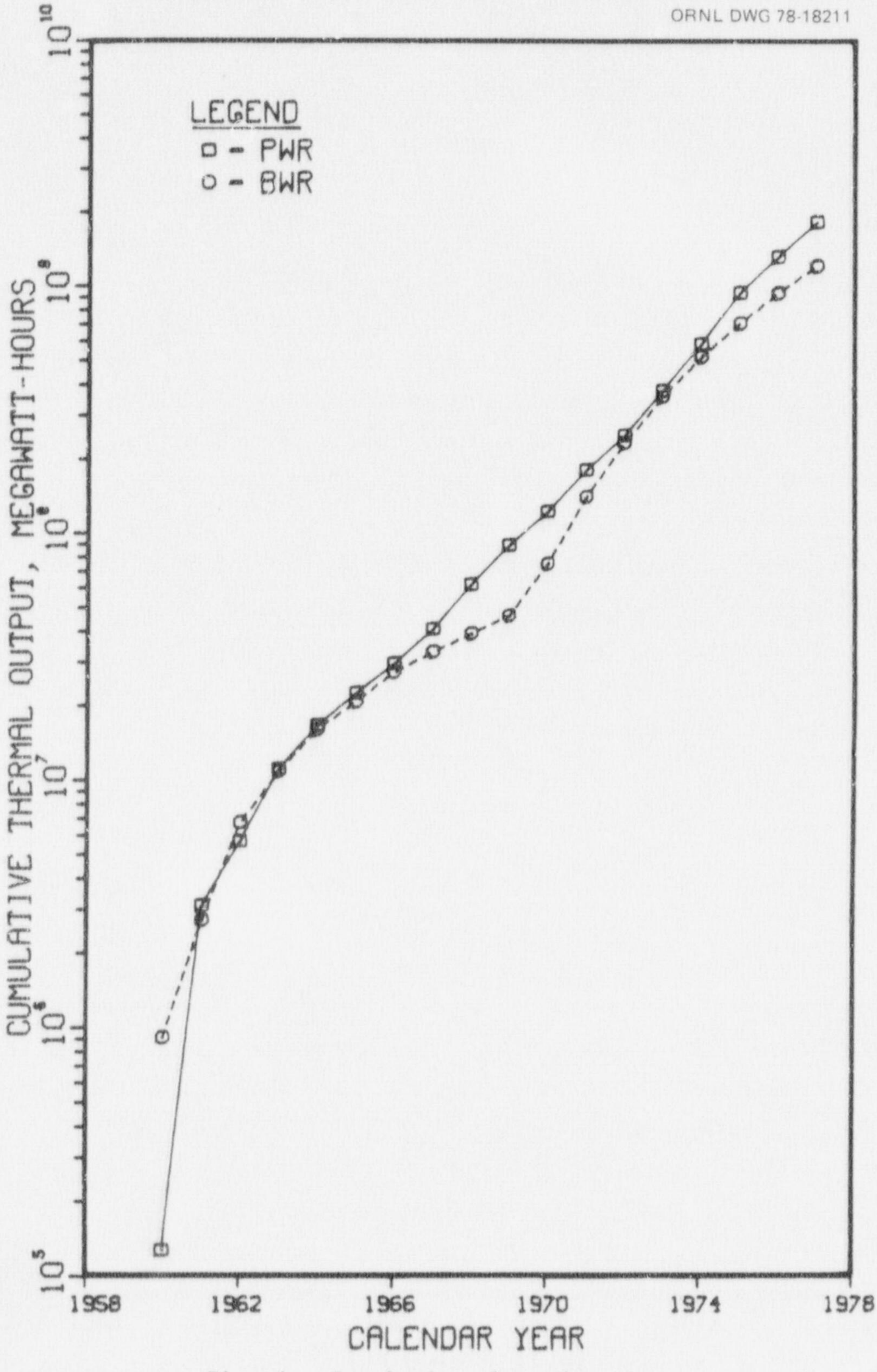

Fig. 4. Cumulative thermal output.

plot of these cumulative output curves is given for both types of reactors and shows that from 1960 to the end of 1977 the cumulative thermal outputs are 1.81×10^9 and 1.21×10^9 MWhr(t) for PWRs and BWRs respectively.

4.2 Radioactivity Shipped

A second variable studied was the total amount of radioactivity routinely shipped offsite to licensed burial grounds. The annual total curies (uncorrected for decay) for PWRs and BWRs are plotted as a function of time in Fig. 5. Again for correlation purposes, cumulative totals were calculated for the two types of reactor, and these results are shown in Fig. 6. The cumulative curves indicate that, as of 1977, the PWRs had shipped only about half the number of curies in waste as the BWRs, that is, approximately 5.8×10^4 vs 1.2×10^5 Ci. Since the nuclides generally were not identified and the times at which the curies were measured were not reported, there are relatively large uncertainties in the curie numbers; thus this difference between PWRs and BWRs may not be as large as it seems.

4.3 Volume of Radwaste

A third variable considered was the volume of the solid radwaste shipped. The annual total cubic meters for PWRs and BWRs are plotted against time in Fig. 7. The curves show a marked increase in the volume of waste shipped by both reactor types since 1970. Calculated cumulative totals for the PWR and BWR waste volumes are shown in Fig. 8. At the end of 1977, these amounted to approximately 5.6×10^4 and 7.7×10^4 m^3 for PWRs and BWRs respectively.

4.4 Comparison Ratios

Comparisons of Ci/MWhr(t), m^3/MWhr(t), and Ci/m^3 for both reactor types are made in the following sections using the data in Figs. 3-8.

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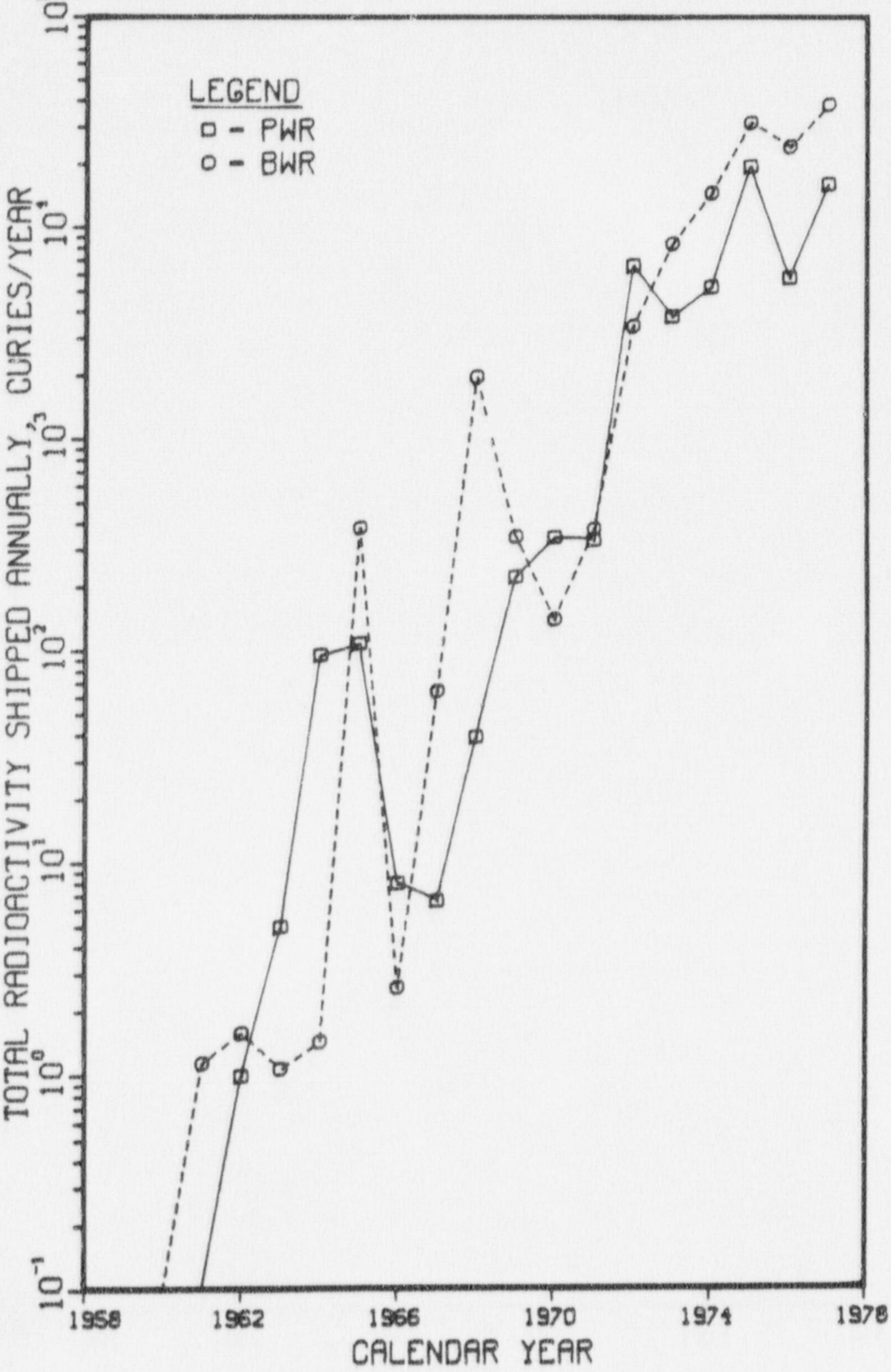

Fig. 5. Total radioactivity shipped annually.

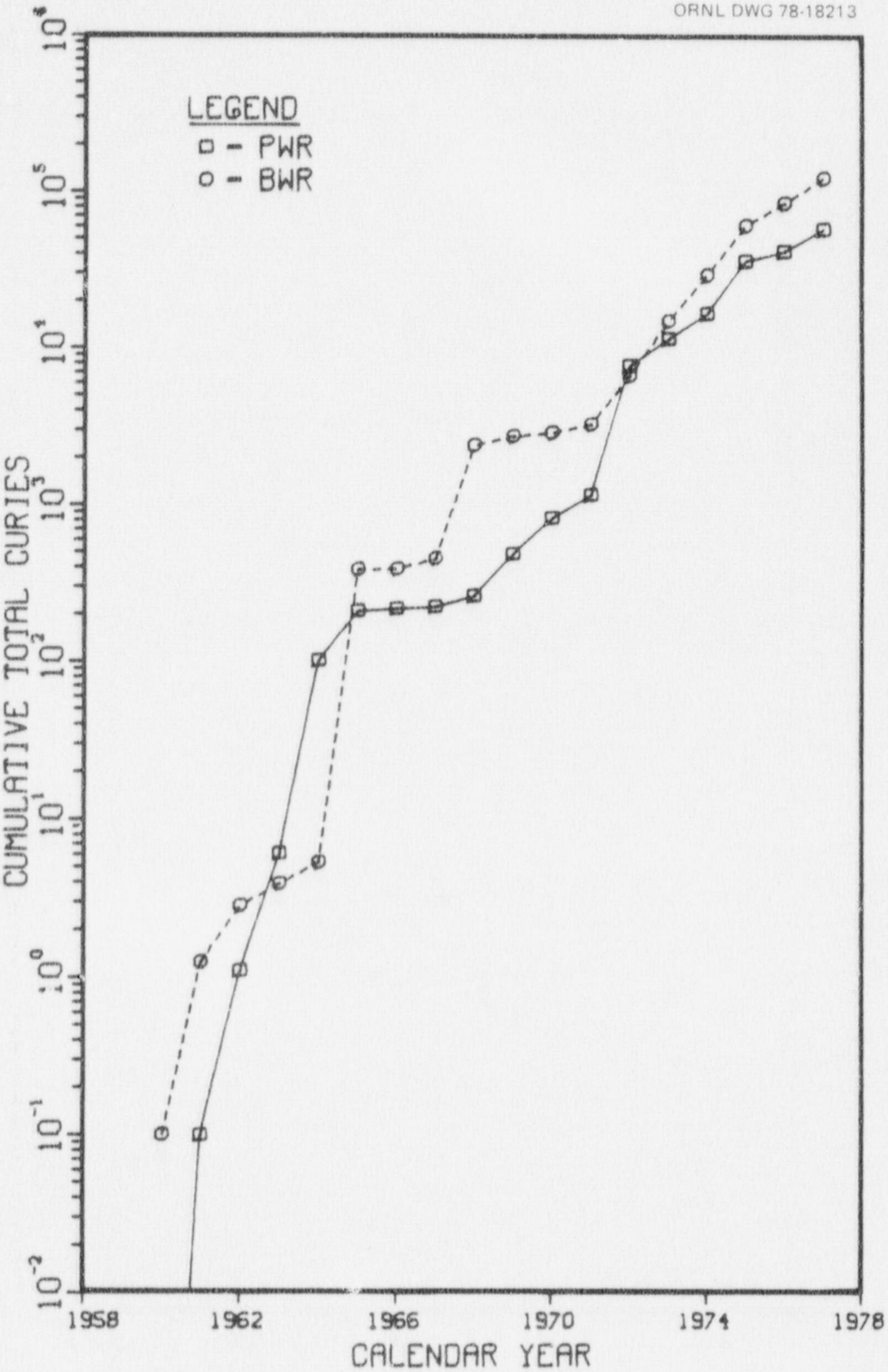

Fig. 6. Cumulative radioactivity shipped in solid waste.

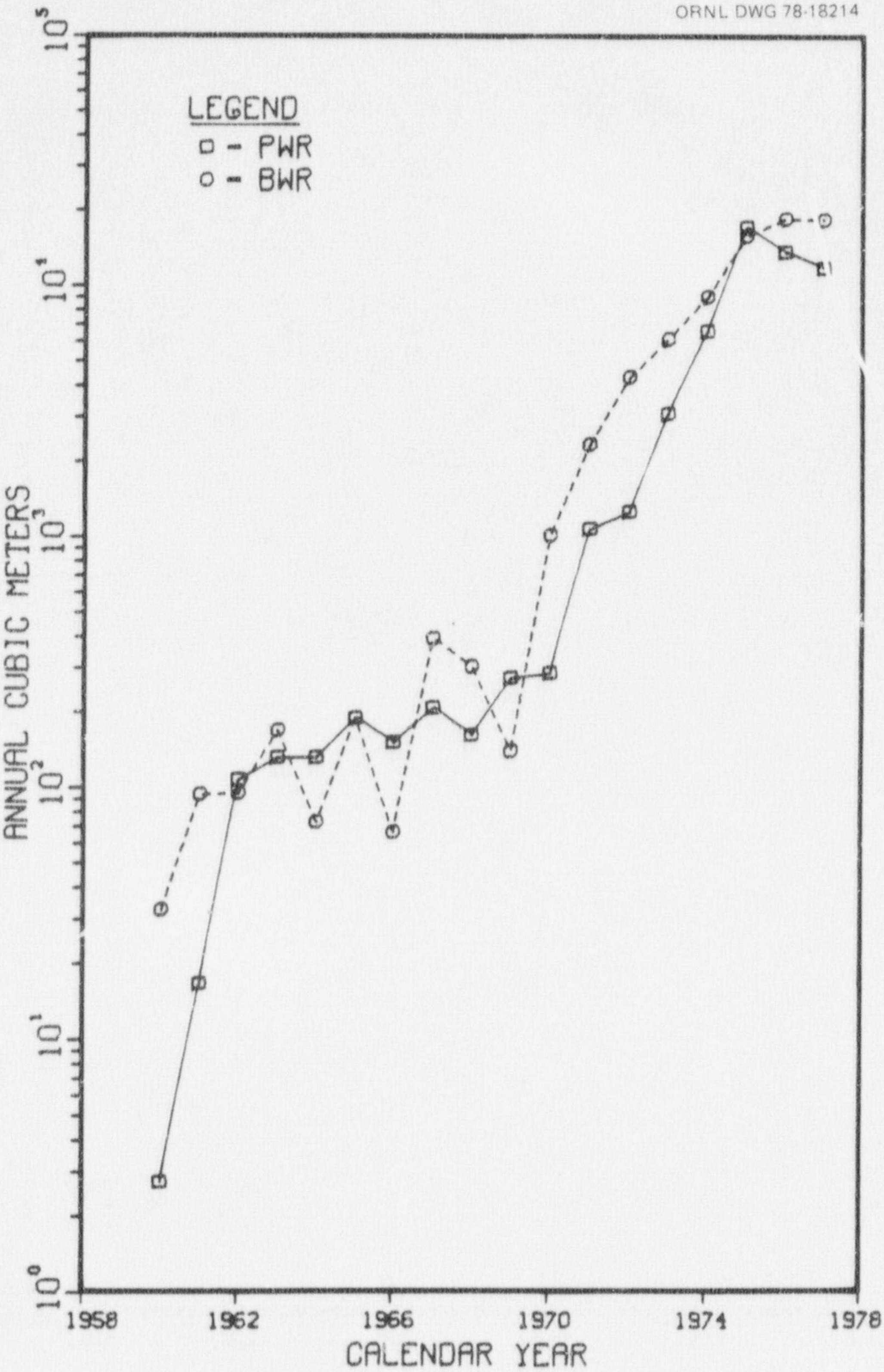

Fig. 7. Total volume of radioactive waste shipped annually.

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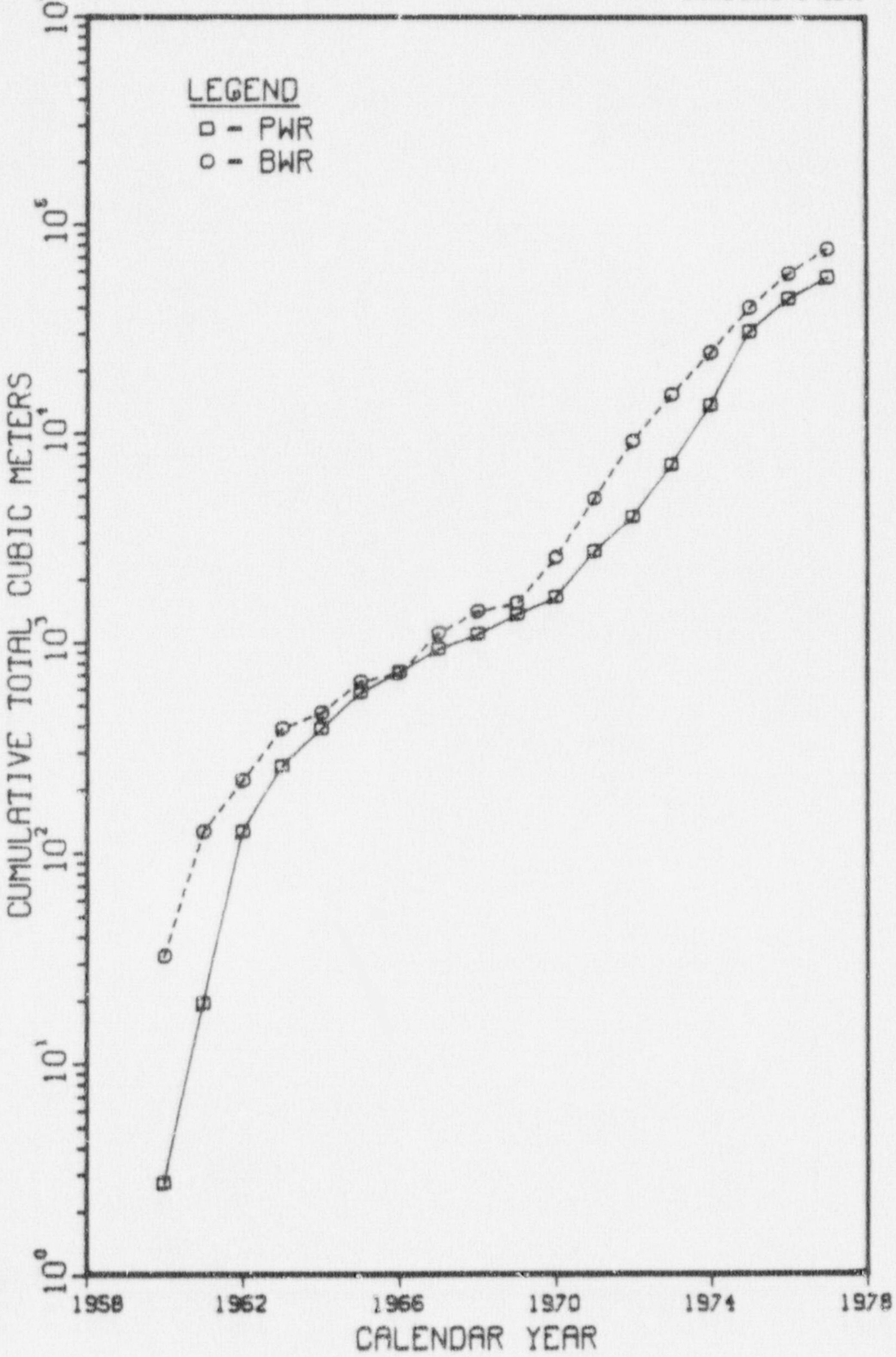

Fig. 8. Cumulative volume of solid radioactive waste shipped.

4.4.1 Curies (or volume)/thermal energy

The curie content of the waste shipped each year (Fig. 5) divided by the thermal output for that year (Fig. 3) is shown in Fig. 9. The volume of waste shipped each year (Fig. 7) divided by the thermal output for that year (Fig. 3) is shown in Fig. 10. The cumulative curies (Fig. 6) and the cumulative cubic meters of waste shipped (Fig. 8) as of the end of each year divided by the cumulative thermal output (Fig. 4) over the same time period are presented in Figs. 11 and 12 respectively. Through the end of 1977, the average number of curies shipped offsite to licensed burial grounds per unit of thermal output is about 3.2×10^{-5} Ci/MWhr(t) for PWRs and 1.0×10^{-4} Ci/MWhr(t) for BWRs (Fig. 11). The cumulative waste volume curve shows that the PWRs have consistently shipped a smaller average volume of solid radwaste per thermal megawatt-hour than the BWRs, and at the end of 1977, the volumes are approximately 3.1×10^{-5} and 6.4×10^{-5} m^3/MWhr(t) for PWRs and BWRs respectively (Fig. 12).

4.4.2 Curies/volume

The activity levels of these wastes expressed in terms of curies per cubic meter for each year are shown in Fig. 13. In Fig. 14, the cumulative totals of curies divided by the corresponding totals of cubic meters shipped at the end of each year by the PWRs and BWRs are shown as a function of time. The values obtained at the end of 1977 for Ci/m^3 are 1.0 and 1.6 for the PWRs and BWRs respectively.

4.5 Number of Shipments

A fourth variable considered was the number of shipments made annually from PWRs and BWRs which are shown in Fig. 15. The cumulative total number of shipments at the end of each year are shown in Fig. 16. Information concerning the size and number of trucks in a shipment is usually not reported. From 1960 to the end of 1977, the PWRs made a cumulative total of 3,741 shipments after a cumulative total thermal output of 1.8×10^9 MWhr(t); corresponding values for the BWRs were

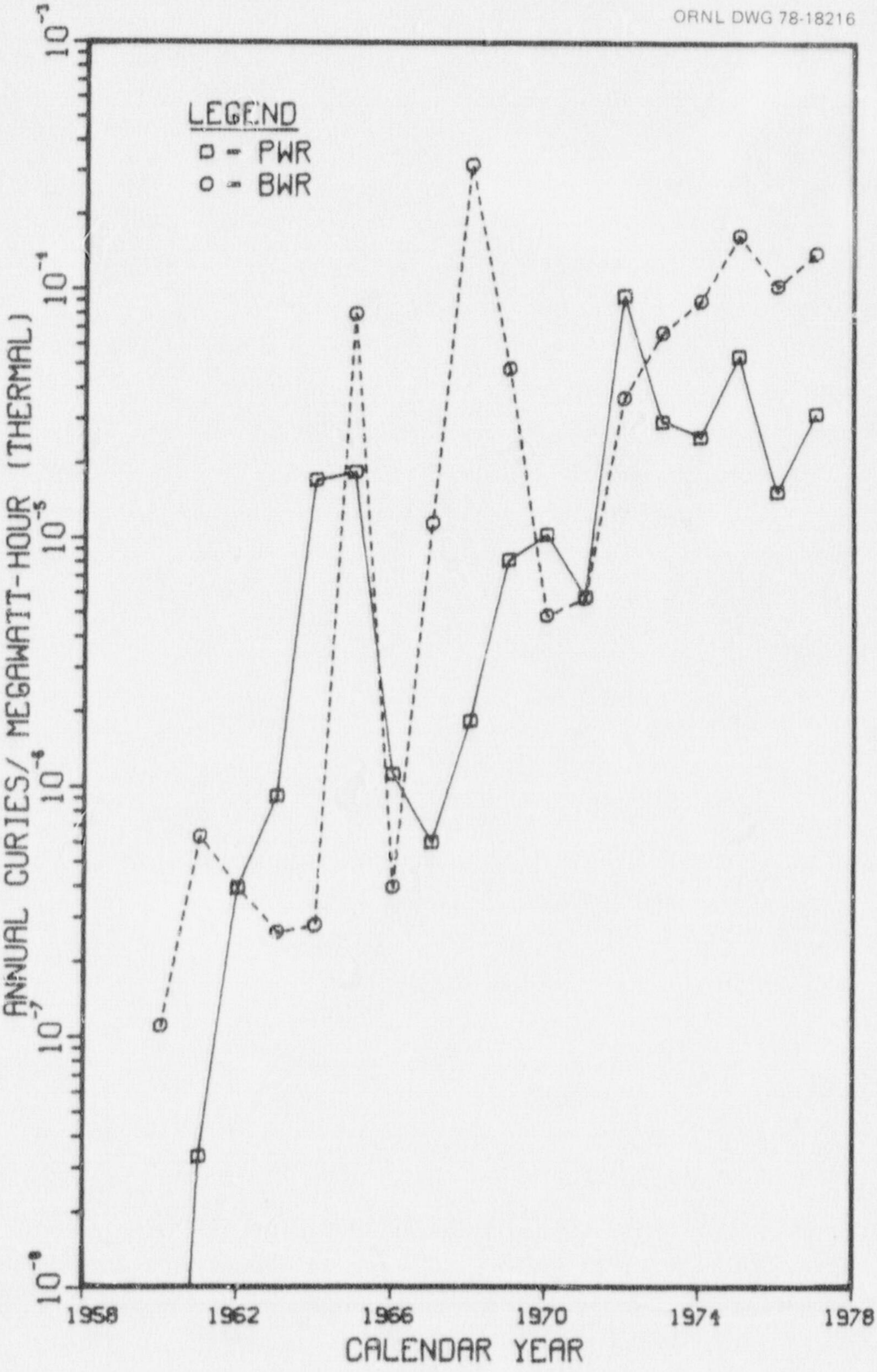

Fig. 9. Annual radioactivity shipped per megawatt hour of thermal output.

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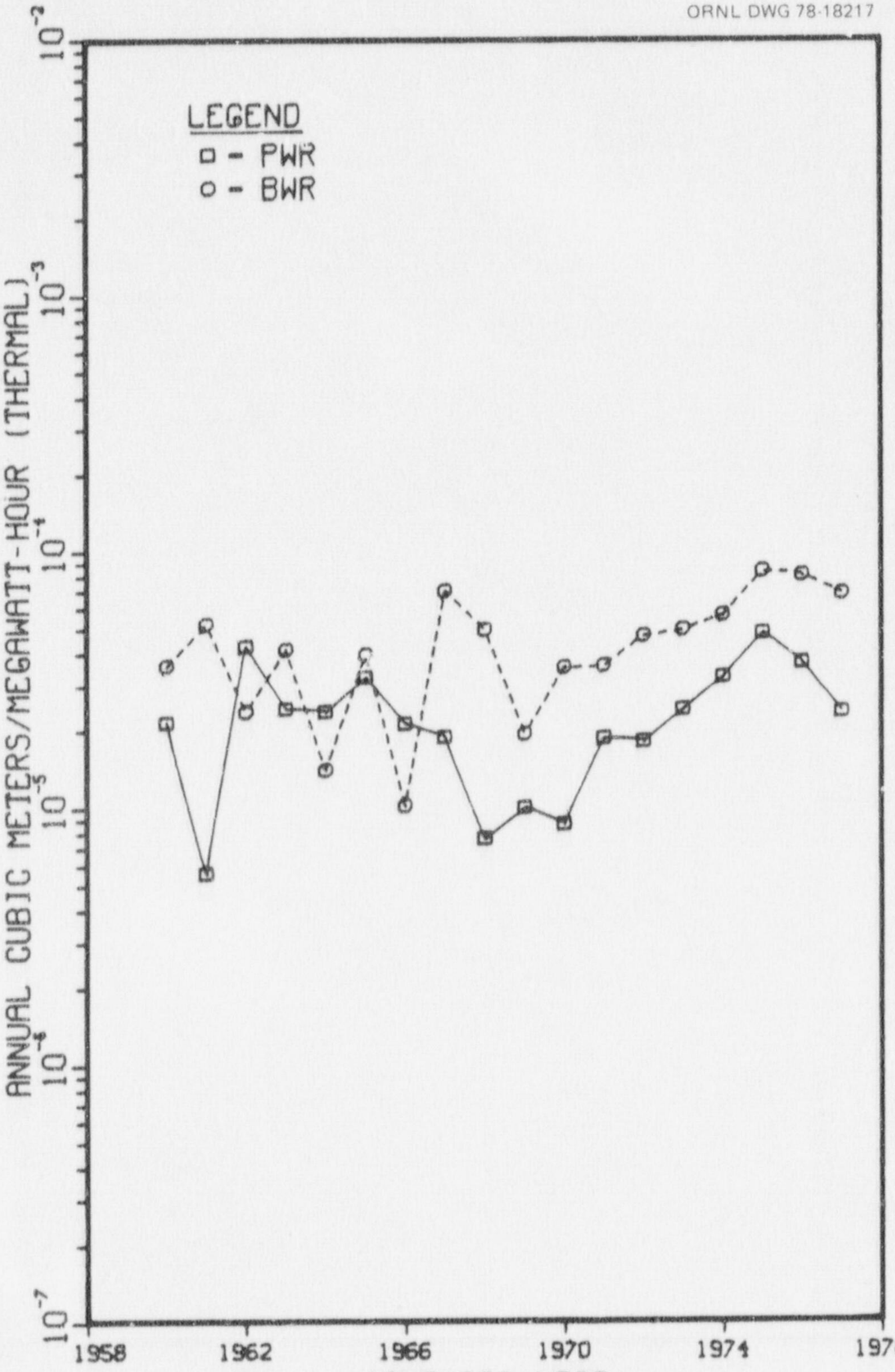

Fig. 10. Annual solid waste volume shipped per megawatt-hour of thermal output.

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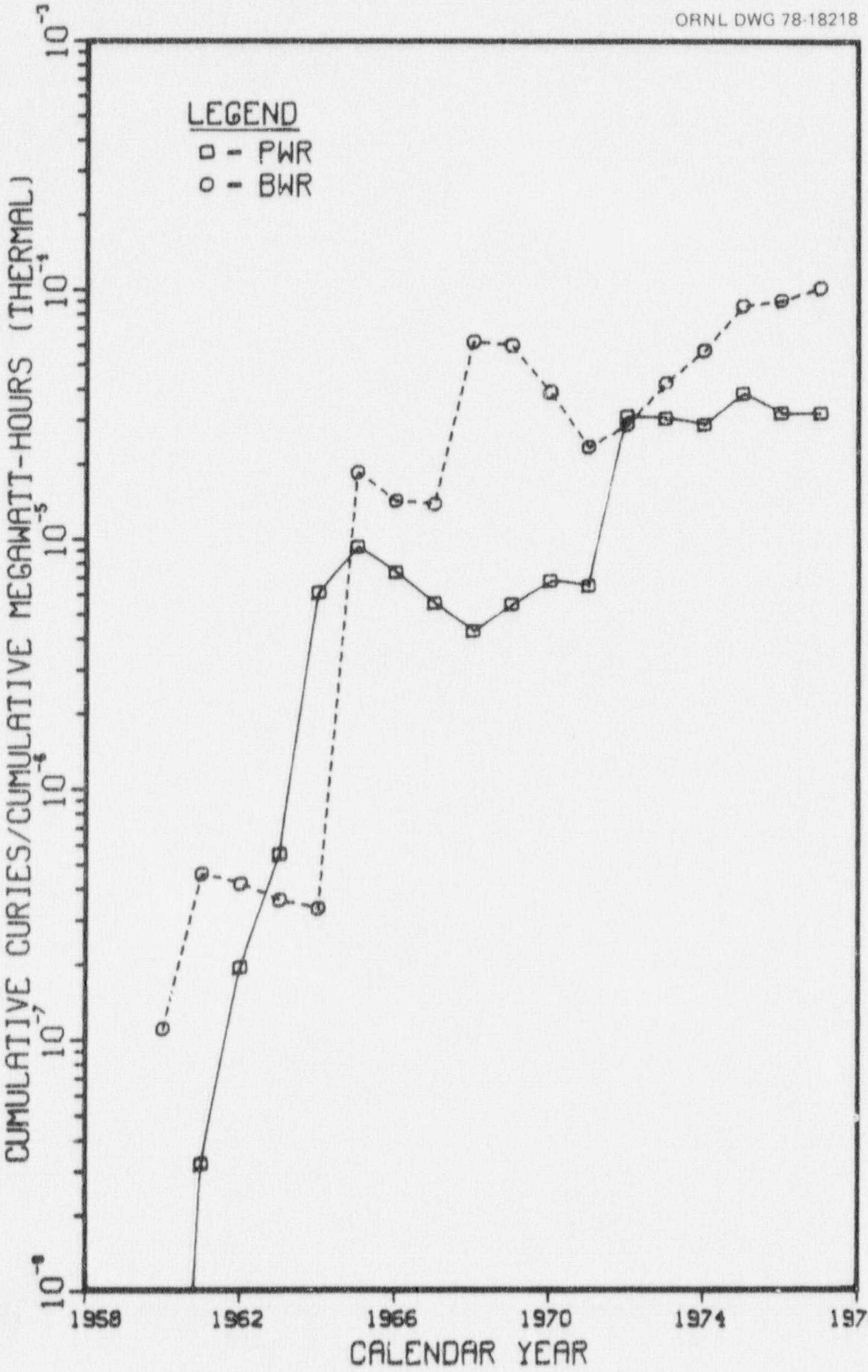

Fig. 11. Cumulative number of curies shipped per cumulative thermal output in megawatt-hours.

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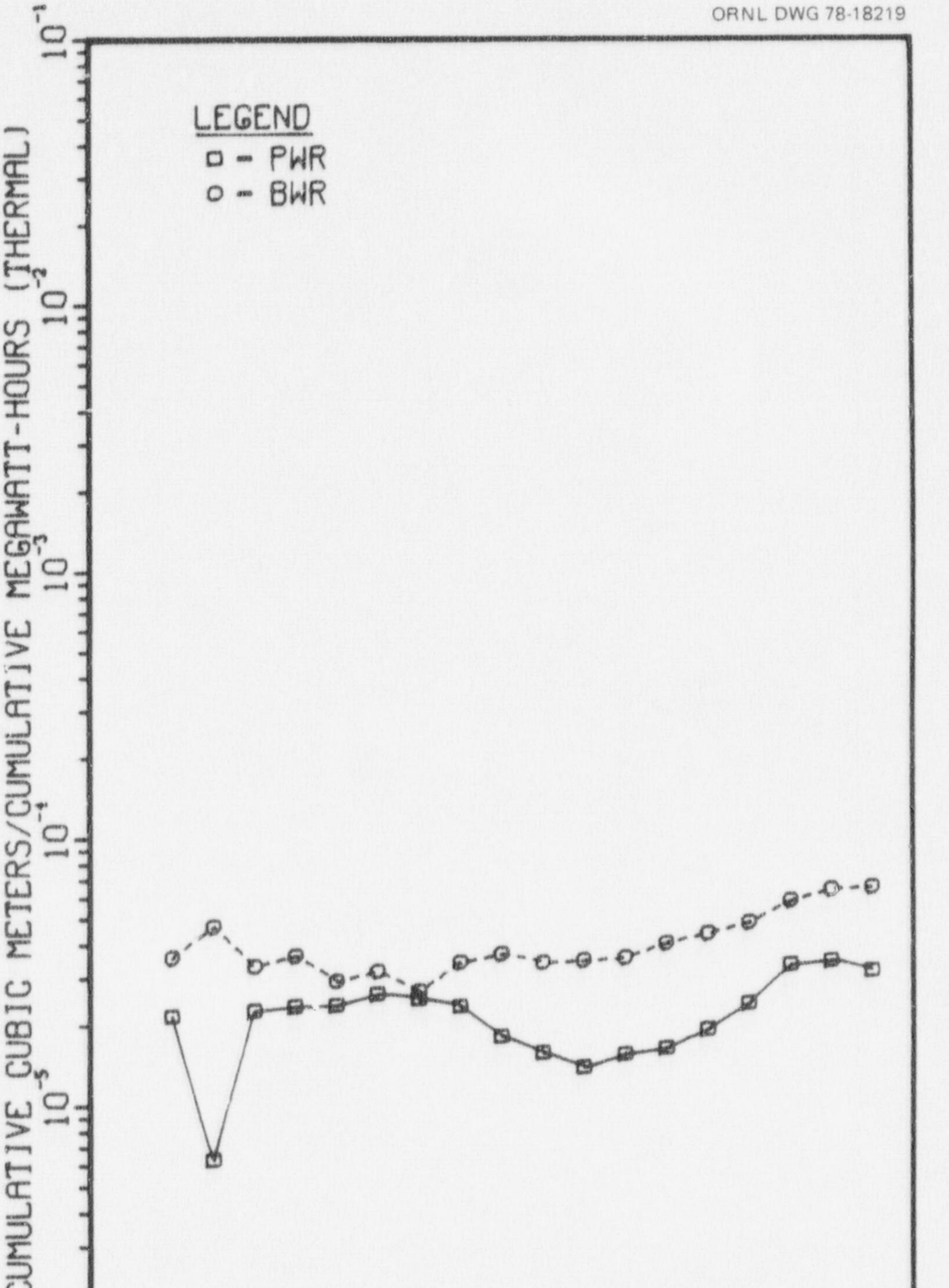

Fig. 12. Cumulative volume of solid waste shipped per cumulative thermal output in megawatt-hours.

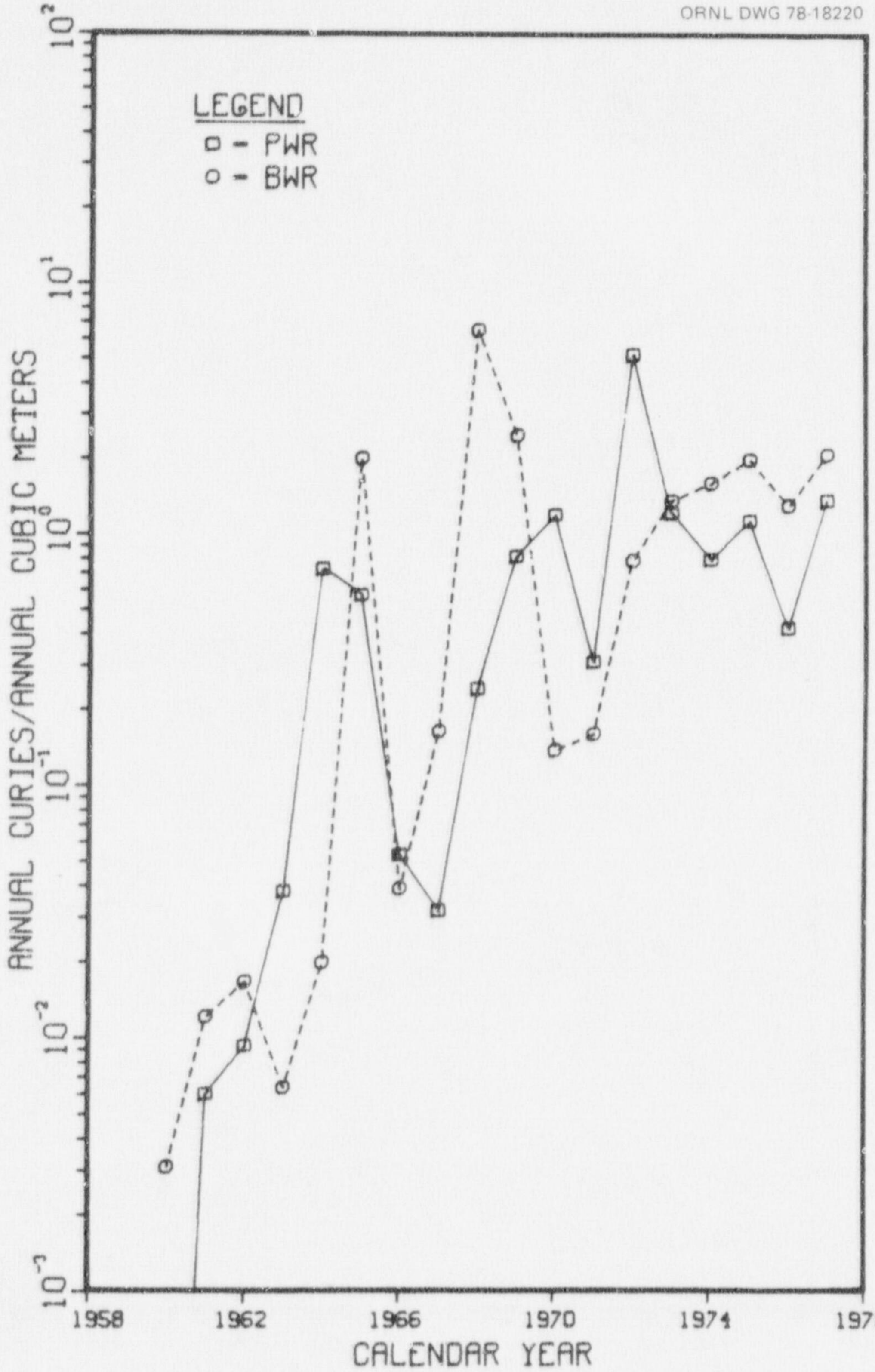

Fig. 13. Ratio of total radioactivity to total volume shipped each year.

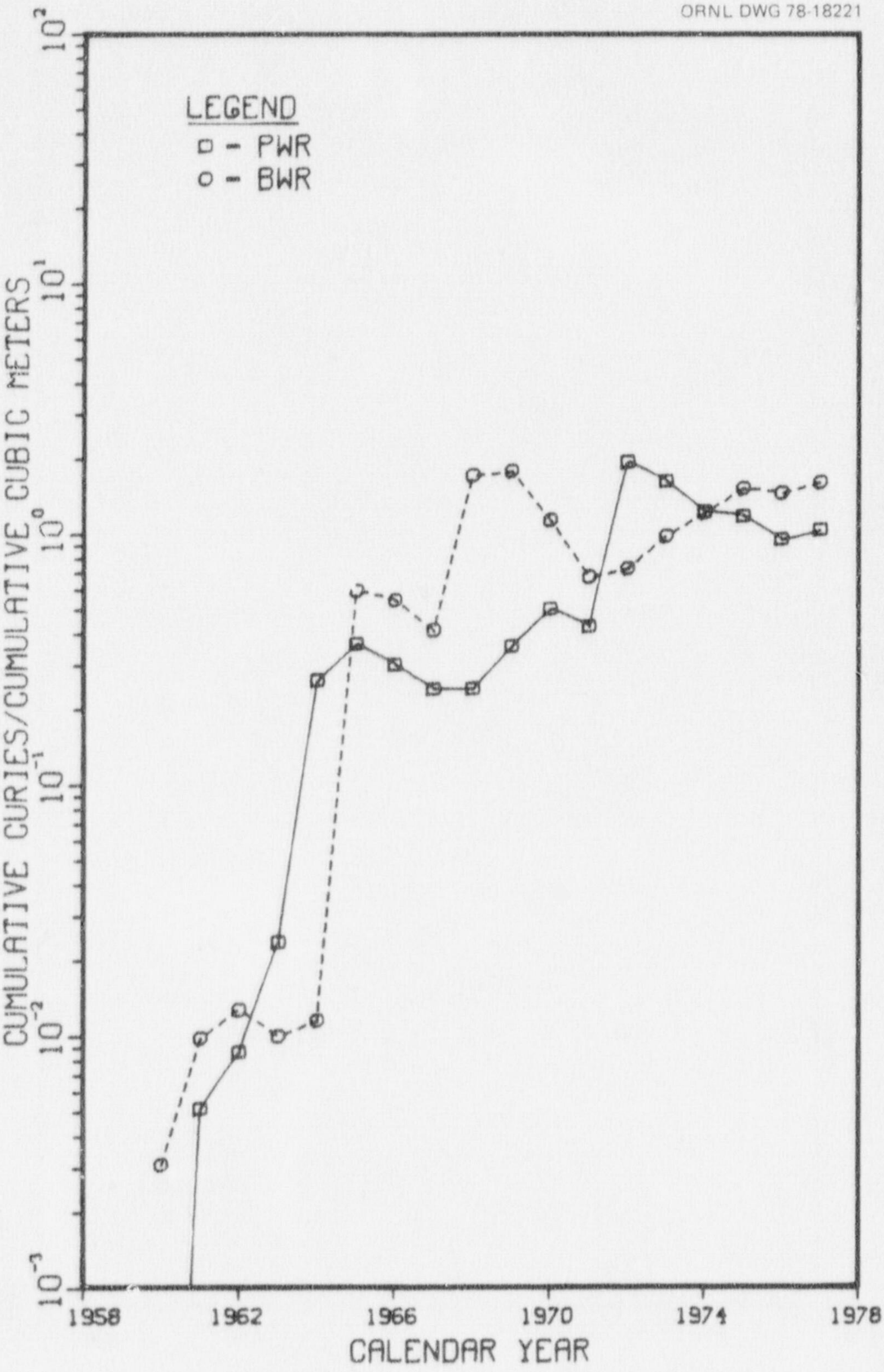

Fig. 14. Ratio of cumulative radioactivity to cumulative volume of waste.

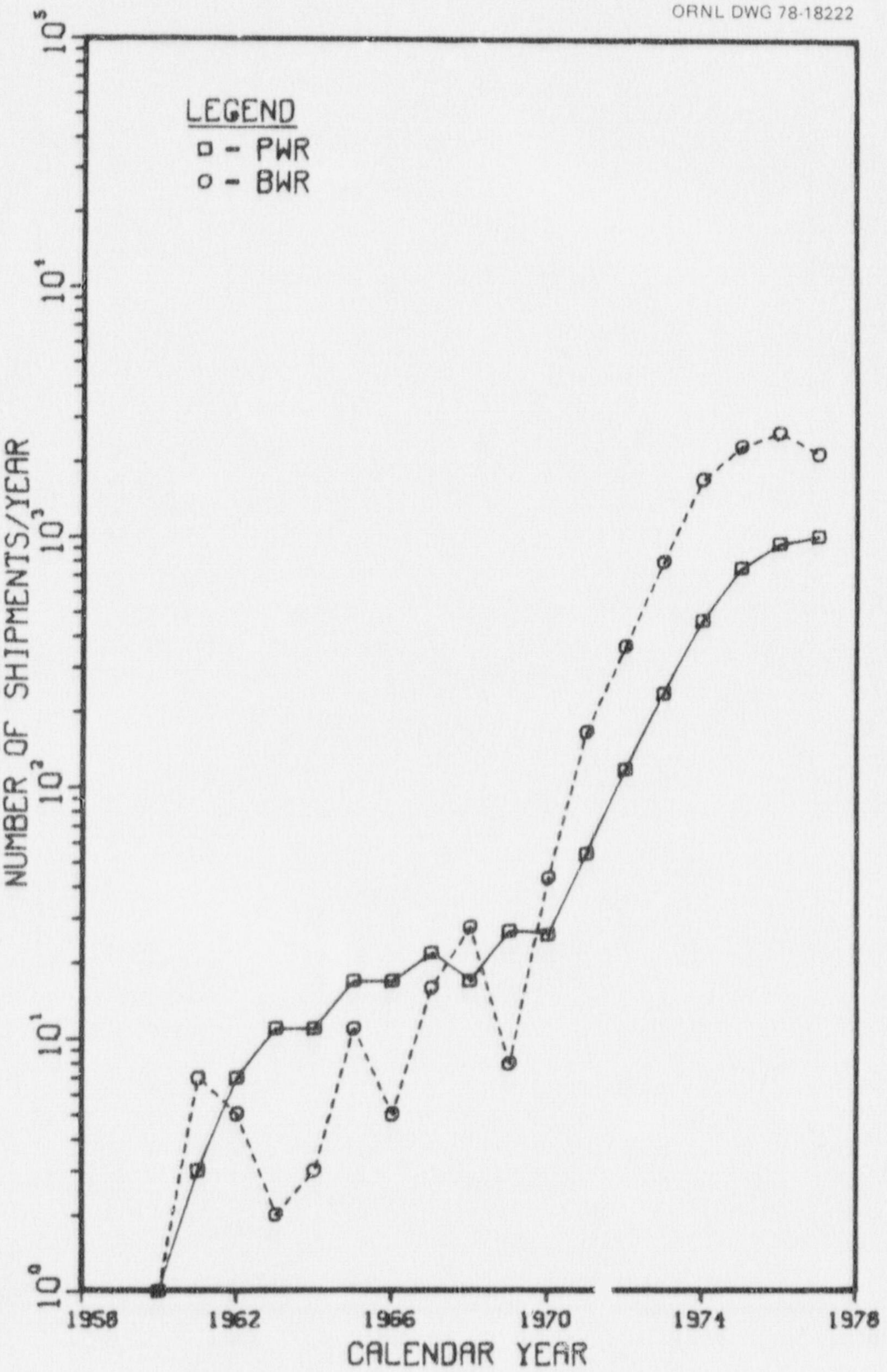

Fig. 15. Annual shipments of radioactive solid waste.

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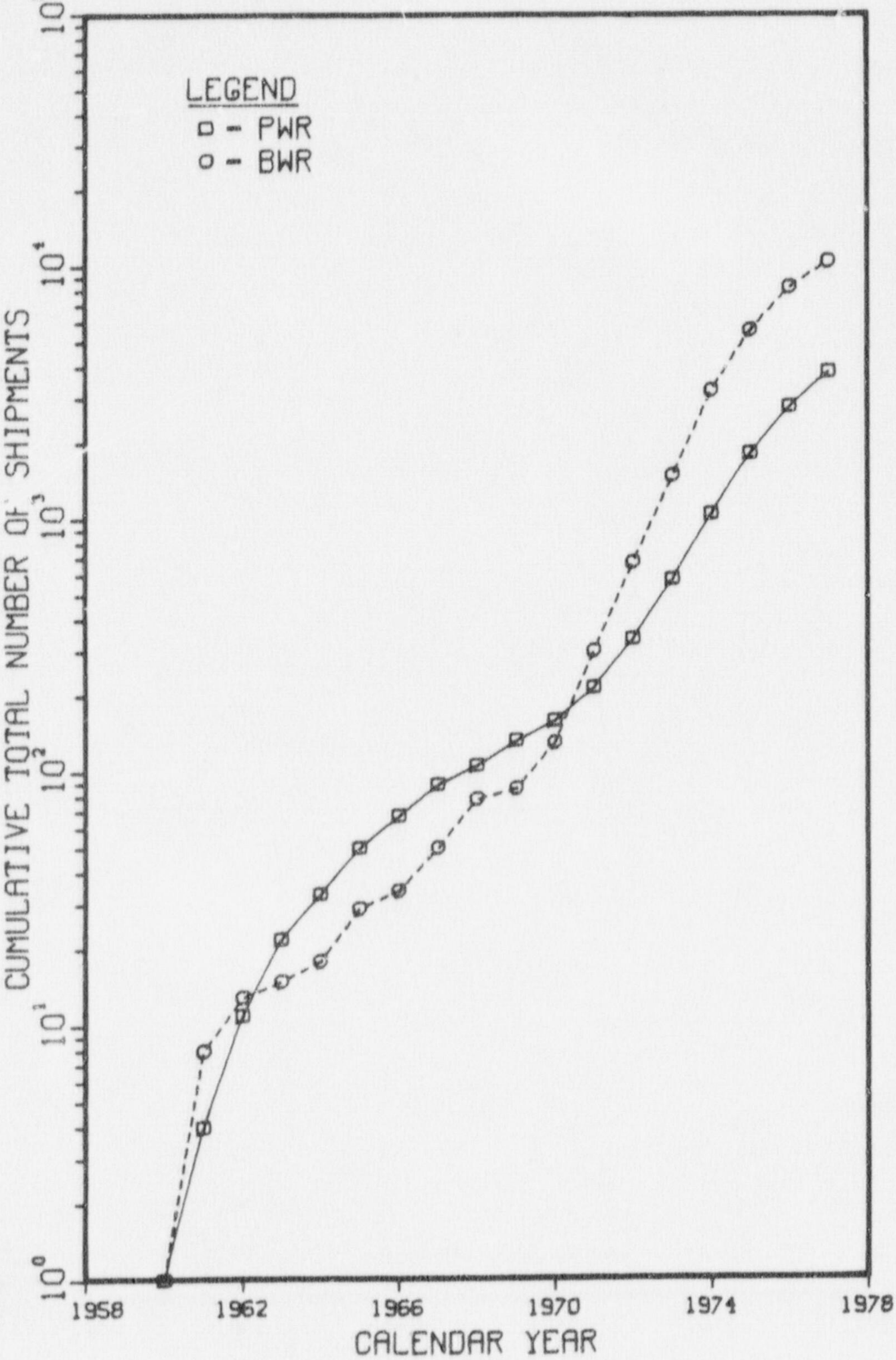

Fig. 16. Cumulative shipments of radioactive solid waste.

10,359 shipments and 1.2×10^9 MWhr(t). The calculated number of shipments per 10^6 MWhr(t) is about 2 for PWRs and 9 for BWRs. From the 1977 cumulative total volumes of solid radwaste shipped from both types of reactors, similar calculations give average values for the cubic meters per shipment of about 15 for PWRs and 7.4 for BWRs.

5. MANAGEMENT OF SOLID RADWASTE AT LWR PLANTS

The boundary between liquid and solid radwaste systems is not easily defined. Most utilities and architect-engineer firms define the start of the solid radwaste system as the tanks or receiving vessels which collect the slurries from the demineralizers, evaporators, filters, and reverse-osmosis equipment. Treatment of these wet wastes can be broken down into four basic subsystems, namely, (1) waste collection; (2) waste pretreatment and volume reduction; (3) solidification agents and mixing; and (4) packaging, container handling, and storage. These will be discussed later in more detail. The flow diagram shown in Fig. 17 for the management of wet and dry solid radwaste at LWRs is based on a similar scheme proposed by the American National Standards Institute (ANSI) Committee on Solid Radioactive Waste Processing.[35] The waste collection subsystem is usually provided by the utility itself or through its architect-engineer. The subsystems required for solidification and packaging are frequently purchased from a single supplier and are chosen on the basis of compatibility with the solids pretreatment subsystems which may be supplied by a different vendor. The interface between the solids pretreatment and solidification subsystems is a critical area in radwaste treatment because the amount of residual water associated with the treated solids can be a factor in determining what solidification method and process control parameters will assure a completely solidified waste product.

Some general considerations apply to all solidification systems. Among these are location of solidification-agent handling equipment in low-radiation areas to minimize exposures to operating personnel; compatibility of the equipment with the chemical and physical properties of the solidification agent employed (e.g., corrosion resistance of cata tanks and piping in liquid systems, and dust containment in systems using cement); and environmental restrictions on solidification-age storage (e.g., relatively low temperature for urea-formaldehyde resin and low humidity for cement).

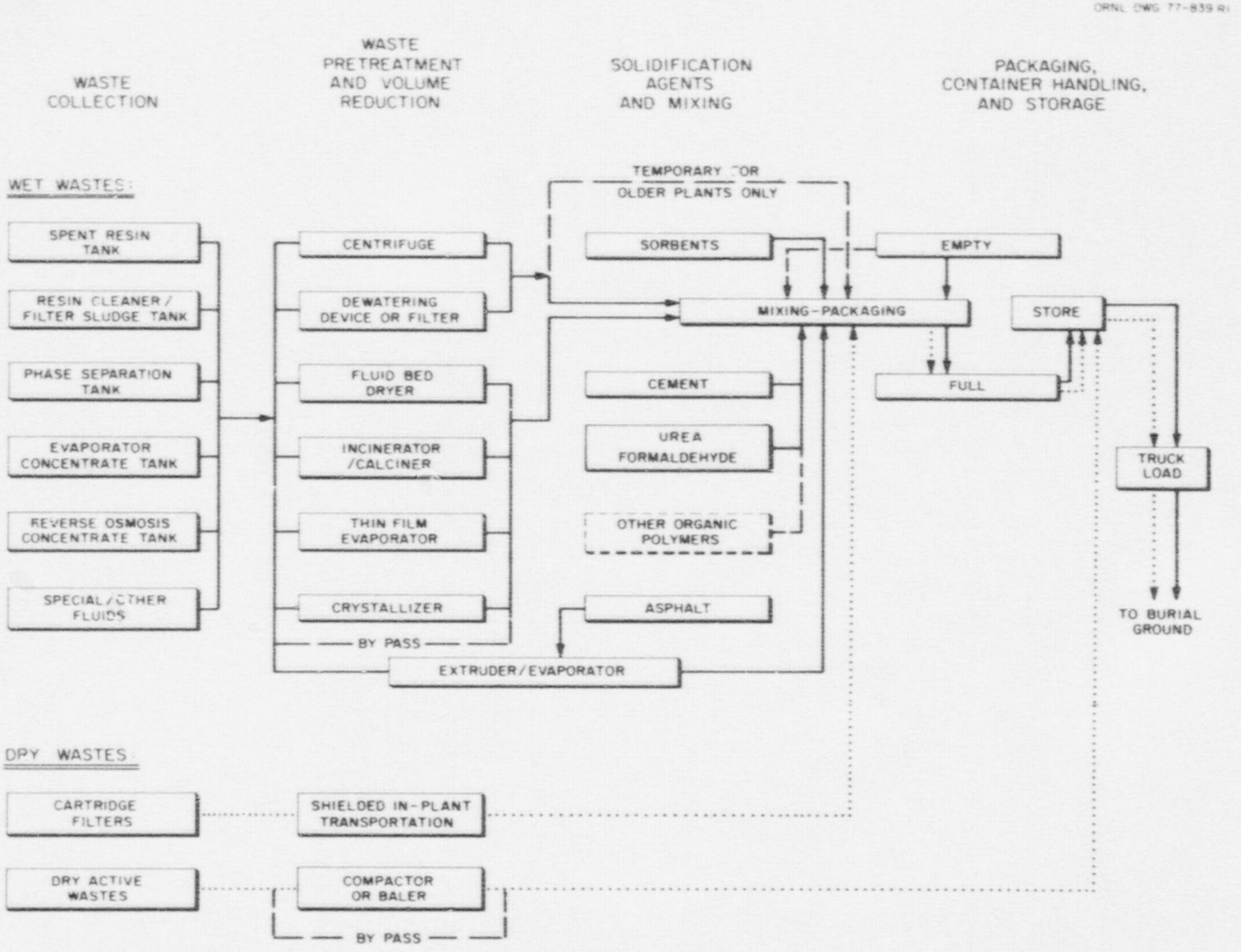

Fig. 17. Flow diagram for radwaste management at light water reactor plants.

5.1 Wet Waste

As mentioned previously, wet wastes consist mainly of spent ion-exchange resins, filter and resin-cleaning sludges, and evaporator and reverse-osmosis concentrates, all of which derive mainly from water treatment or purification of liquid streams in LWR plants.

5.1.1 Collection

Adequate tankage for waste collection is essential to unhampered power plant operation. Under normal circumstances, provision for at least 60 days of radioactive decay for primary system wastes[36] such as reactor water cleanup or chemical and volume control system resins or sludges prior to solidification is used for eliminating the bulk of short-lived nuclides. For other wastes which ordinarily have much lower radioactivity levels (e.g., radwaste filter sludges and evaporator concentrates), 30 days decay is usually sufficient.[36] In addition to providing time for radioactive decay, the waste collection tanks can also provide surge capacity to accommodate periods of abnormally high waste generation or outages in the solid waste processing system. The tanks are usually designed with capability to receive all liquid inputs to the waste solidification facility including auxiliary streams under all anticipated conditions.

5.1.2 Pretreatment and volume reduction

Pretreatment equipment for solids and liquids is designed to reliably process the expected range of input streams. Special design considerations may be necessary to ensure that dewatered or concentrated radioactive solids can be handled remotely with minimum equipment contact by operating and maintenance personnel. Where manual access to solids pretreatment equipment is necessary, the capability for completely flushing all radioactive materials from the affected parts must be designed into the system. If compressed gases are used for the drying or transport of radioactive materials, appropriate air filtration devices are needed to remove particulates that may be entrained in the exhaust gas stream.

Waste pretreatment is basically a volume reduction process serving to minimize the quantity of waste to be solidified and shipped offsite. The wet wastes generated at a nuclear plant contain large volumes of water. Removal of this water from spent bead or powdered resins and filter sludges can be accomplished by any of several methods, among them: decantation (either in the collection tank or in a separate decant tank), centrifugation, or filtration (see Figs. 1 and 2). According to ref. 37, decantation or in-tank filtration can reduce the water content of the solids to the range of 70 to 80 wt %. The centrifuge is more efficient at water extraction and is capable of producing solids containing only 50 wt % water. Flat-bed and centrifugal-discharge filters give solid products containing 50 to 70 wt % water. Most evaporator concentrates at BWRs are 10 to 25 wt % sodium sulfate, whereas at PWRs they are 10 to 12 wt % boric acid. In the past, usual practice has been to solidify these slurries without further pretreatment.

As previously mentioned, the amount of residual water is intimately related to the solidification procedure selected. A waste containing 25 wt % solids is at about the right concentration for incorporation in cement. If the water content of the pretreated slurry is 50% or less by weight, some water or liquid waste would probably have to be reintroduced to maintain the consistency required for cementing. Some BWRs with centrifuges have added evaporator concentrates to dewatered filter sludge for the purpose of providing the additional water needed to make a cement product.

In recent years, volume reduction has become an increasingly important factor in nuclear plant waste management since operating data have shown that solid waste volumes are much larger than originally expected while disposal costs have continued to rise.

Several types of volume reduction equipment are available that can produce solids from wet wastes (e.g., evaporator concentrates) with final water contents between almost nothing and 50 to 60 wt %. The fluid-bed dryer, the fluid-bed incinerator/calciner, the thin-film evaporator, and the crystallizer are examples. The first two are discussed in this report, while the latter two are discussed in ref. 20.

Interfacing these units with a cement solidification process can present the same problem (i.e., insufficient water to make a workable paste) as described above for combining centrifugation with cementation. Similarly, other factors, which may or may not depend upon residual water content, must be taken into account when one of these volume reduction methods is tied to a solidification system using organic polymers such as urea-formaldehyde resins or water-extensible polyesters. The asphalt extruder/evaporator can unite volume reduction and solidification in a single operation, but in some cases it may be advantageous to precede the extruder with a fluid-bed dryer or a thin-film evaporator.

A *fluid-bed dryer* with an optional incinerator (Fig. 18) was developed[38] to produce anhydrous, free-flowing, granular solids from nuclear power plant liquid radwastes. For example, the initial concentration of evaporator concentrates typically ranges from 10 to 25 wt % salts (Na_2SO_4, Na_3PO_4, $Na_2B_4O_7$, or $NaBO_2$). Such wastes can be processed by the fluid-bed dryer at rates of up to about 50 gal/hr.[38] The granular solid product from the dryer may be immobilized by incorporation in asphalt or in one of the other solidification agents described later in Sect. 6.

A volume reduction system that is both a *fluid-bed dryer (calciner) and incinerator* has been developed[39] for treating radioactive wastes. The unit operates at a higher temperature than a fluid-bed dryer alone, and it can burn spent ion-exchange resins as well as produce anhydrous granular solids from evaporator concentrates. Also, solid combustible wastes such as paper, rags, and contaminated clothing can be shredded and then injected into the incinerator/calciner. A silver zeolite bed, for removal of iodine from the off-gas, is located between the final high efficiency particulate air (HEPA) filter and the discharge blower. This off-gas cleanup is especially important when ion-exchange resins are burned. A layout drawing of this incinerator/calciner volume reduction system is given in Fig. 19. The dry solid product from the system is removed by gravity and can be incorporated into one of the immobilization agents considered later in this report. Installation of an incinerator/calciner is now planned for the Nine Mile Point Nuclear Power Plant.

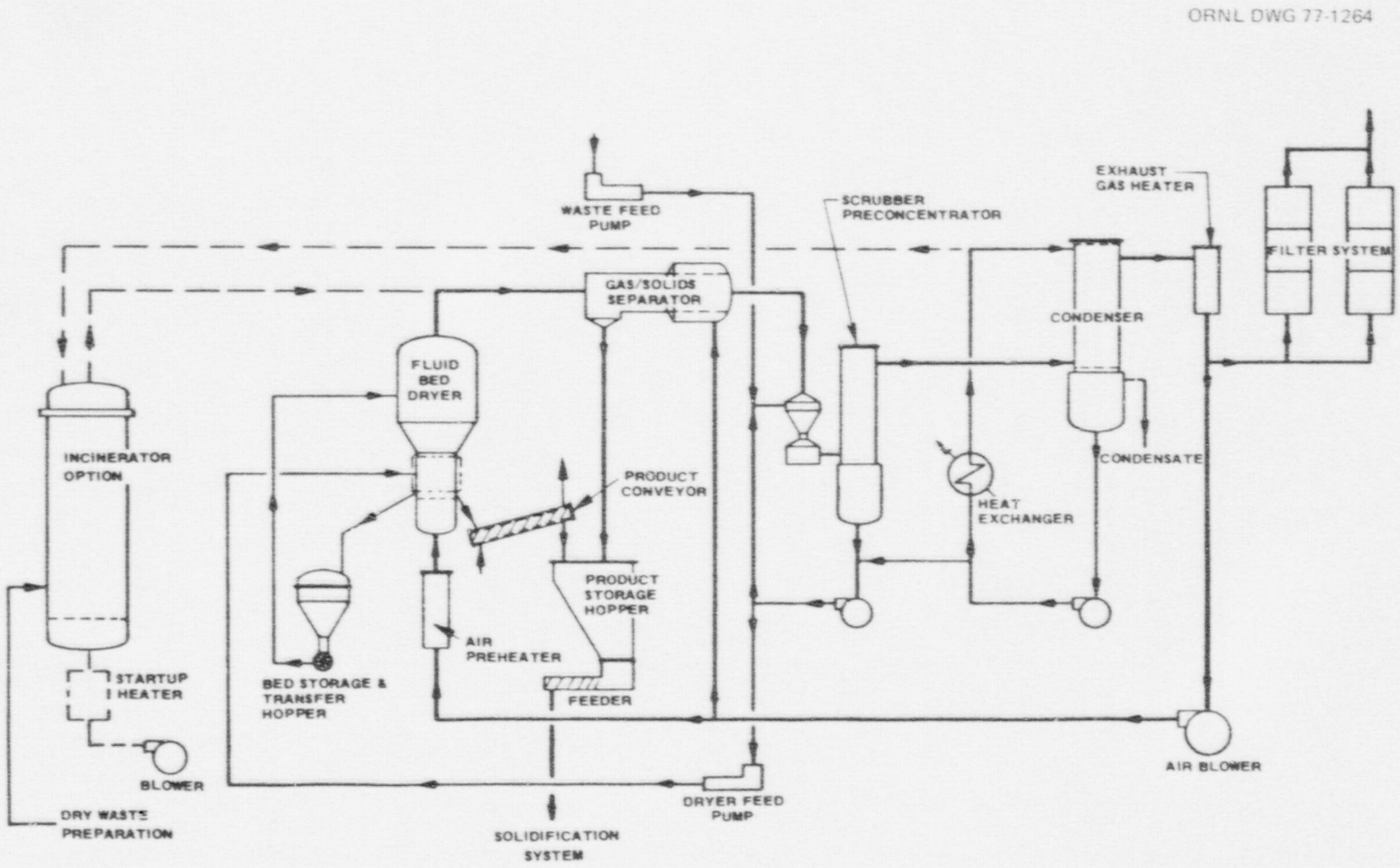

Fig. 18. Aerojet fluid-bed dryer volume reduction system with optional incinerator.

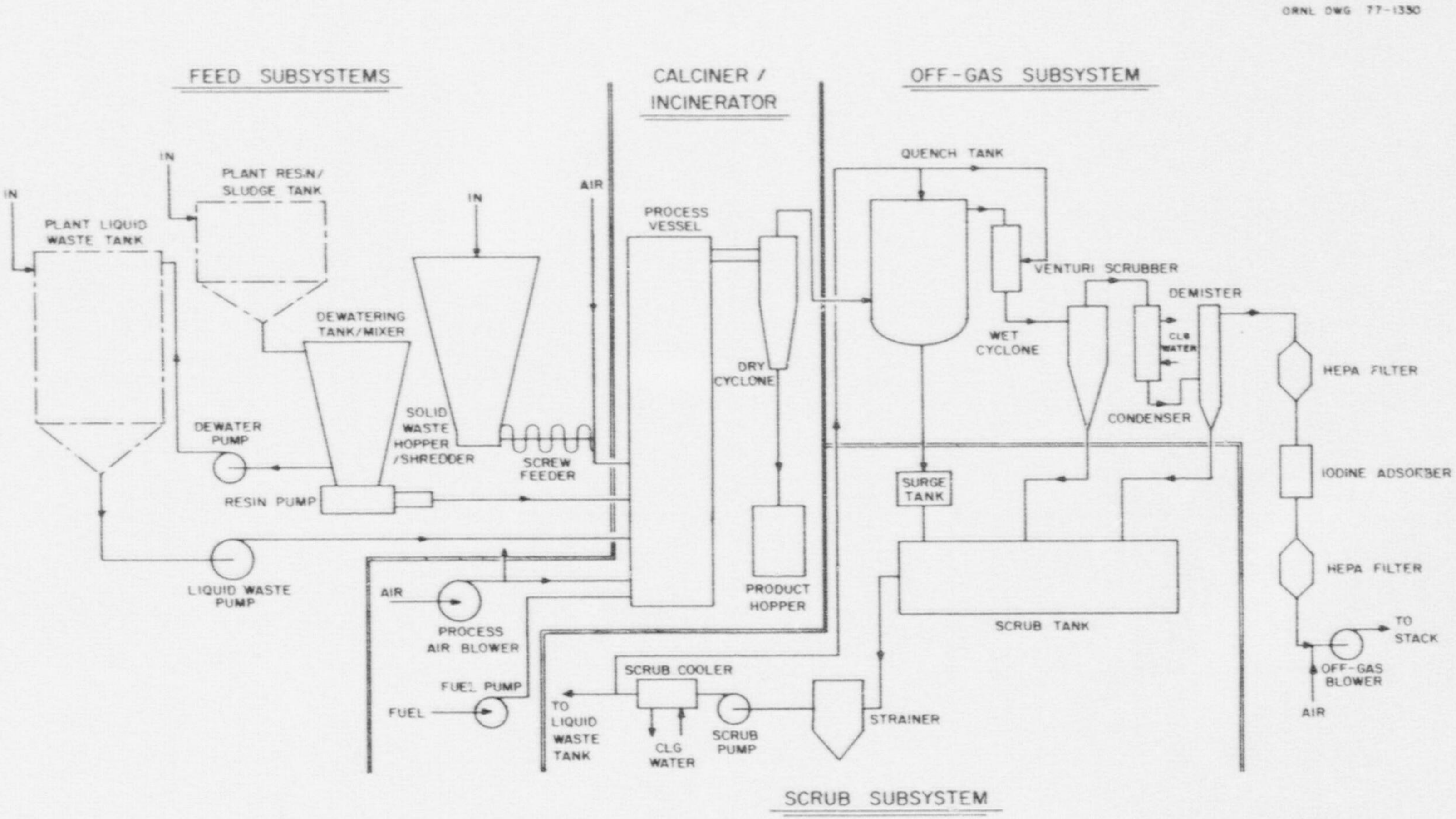

Fig. 19. Energy, Inc./Newport News Industrial Corp. fluid-bed incinerator/calciner volume reduction system.

The *extruder/evaporator* radwaste treatment system combines volume reduction and solidification with asphalt (bitumen) in a single step.[40] Wet radwastes including filter sludges, spent resin slurries and/or slightly alkaline (pH 8 to 10) evaporator concentrates at ambient temperature, and preheated asphalt (∿150°C) are fed simultaneously into a steam-heated (140 to 175°C) screw extruder (see Fig. 20) where the contained water is evaporated and vented through steam domes. It is reported[37] that by this method it is possible to evaporate 99.5% of the water at rates of about 50 gal/hr. The mixed asphalt and solids product can be discharged to a 55-gal drum or other shipping container for offsite disposal. The weight ratio of bone-dry solids to asphalt is generally recommended at roughly 1 to 1, although ratios as high as 1.5 to 1 are sometimes still acceptable.[37] The solids-to-asphalt ratio not only governs the amount of volume reduction achieved but also determines the amount of radioactivity present in the final solidified product. This system has been widely used in Europe (especially Germany and France) for many years, and more recently the Canadians, Argentines, and Mexicans have ordered units for processing nuclear power plant wastes. Midland Nuclear Plant (Units 1 and 2) is the first U.S. power station to contract for installation of an extruder/evaporator.

5.2 Dry Waste

The dry radwaste generated at nuclear power plants can be classified as either compactable or noncompactable, combustible or noncombustible, and as combinations of these. Although the treatment of dry wastes varies somewhat from plant to plant, only a few practices are in general use. The dry wastes under consideration in this discussion are either noncompactable and noncombustible (e.g., contaminated equipment and tools) or compactable and combustible (e.g., paper, rags, plastics, etc.). A description of ways in which these wastes are treated at most nuclear power plants will be given in the next few sections.

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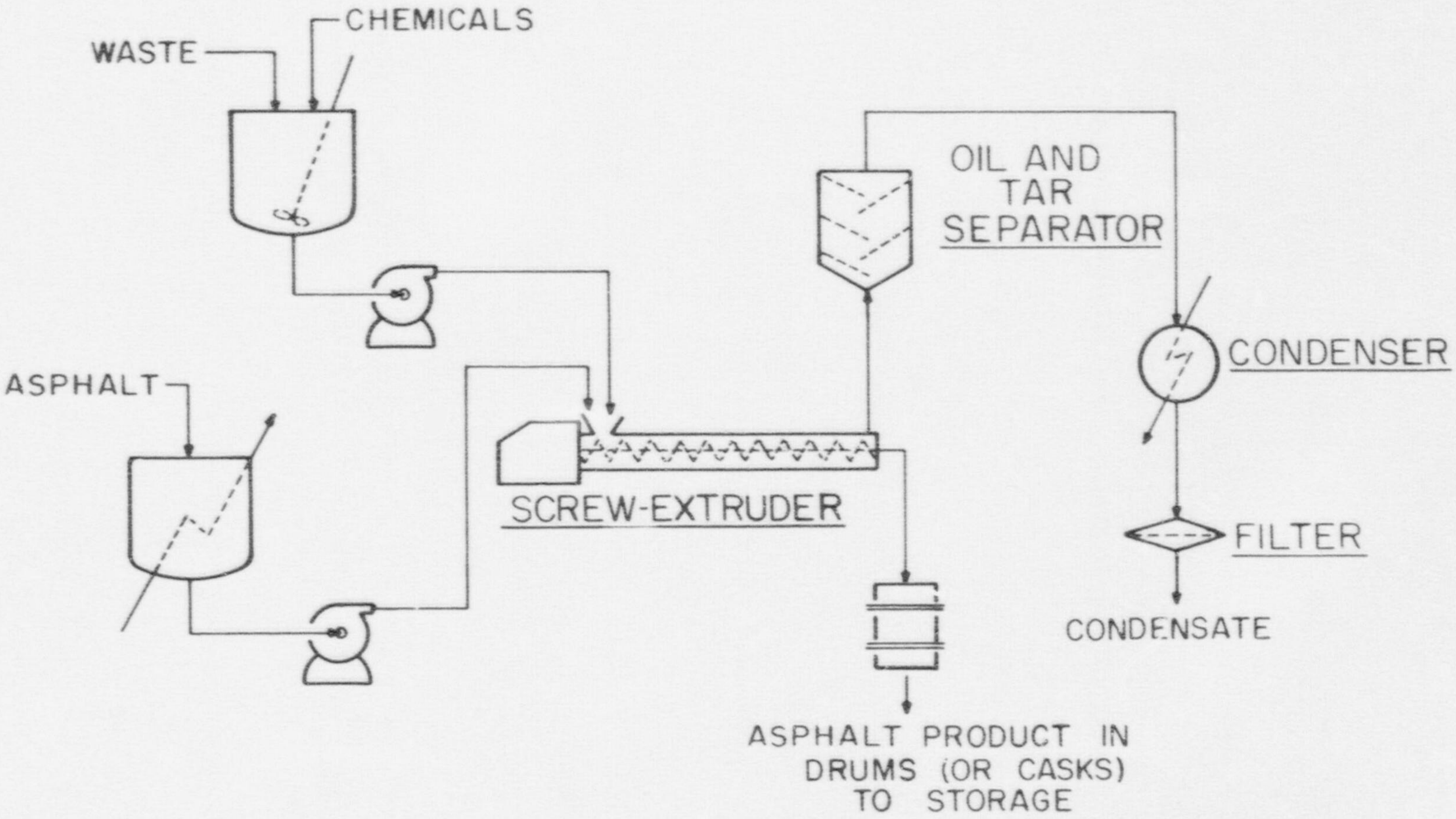

Fig. 20. Werner & Pfleiderer extruder/evaporator process for volume reduction and solidification in asphalt.

5.2.1 Noncompactable/noncombustible

The ordinary solid wastes that are in the noncompactable/noncombustible category are usually not generated routinely and are therefore managed according to need. They may be either packaged individually or included with other solid wastes for shipment offsite.

Spent filter cartridges are routine wastes that are difficult to classify. They are sometimes considered as "dry" wastes (see Fig. 17) that are noncompactable and noncombustible. However, because of the way in which they are prepared for storage and burial, spent cartridges may be included with "wet" wastes as they are elsewhere in this study (see Appendix A). Filter cartridges are routinely used in rather large numbers (i.e., estimated as high as 175/yr)[41] in a modern twin-unit PWR power plant but are seldom used in BWR plants. The cartridges are changed out on the basis of either high pressure drop or a limiting high radioactivity level. Some spent filter cartridges at PWR plants are highly radioactive, with contact dose rates of several R/hr being common.[19] Because of their high levels of radioactivity, the spent cartridges are put into portable lead shields immediately upon removal from service. The equipment used in this operation is usually custom-designed (e.g., remote control apparatus or special-purpose, long-handled tools) because, in many instances, the filter cartridges used throughout the plant are not standardized. The massive shields containing the spent cartridges are transported by overhead crane to the packaging station, where they are collected in shielded storage or shipping containers. At this point, the spent cartridges are commonly imbedded in some solidification agent or packed in sorbent materials. The storage or shipping casks containing the packaged cartridges are then moved to an onsite storage pit to allow for radioactive decay; in some cases, however, they may be shipped immediately for offsite burial.

5.2.2 Compactable/combustible

During refueling and maintenance operations, especially large volumes of compactable and/or combustible wastes are generated at nuclear power plants. The most common way of preparing these wastes for offsite shipment has been to compact them in 55-gal drums. However, at least one older BWR plant (Humboldt Bay) merely collected the bulk of these wastes in 4.5-ft^3 fiberboard boxes which were shipped offsite with no further treatment. Zion (a large, newer PWR plant) has no compactor and follows a similar practice, except that 128-ft^3 wooden boxes are used for transport of these wastes. One of the older PWR plants (Yankee-Rowe) is the only operating reactor in the United States where incineration is used to treat some dry combustible wastes, although this practice has been widespread in Europe for many years. At Yankee-Rowe the incinerator is not used for burning the combustible wastes generated during refueling operations.

Currently, nearly all LWRs in the United States have some type of compactor for compressing dry compactable radwaste into 55-gal drums (so-called drum compactors). Problems most often encountered in this operation are in-building dust releases and occasional bent or broken platens due usually to poor waste segregation. Most compactors used at power plants have been designed with a 20,000-lb maximum force.

To alleviate the most prevalent problems encountered with commercial drum compactors, a unit with a 30,000-lb force, and featuring hinged doors on the loading table and on the extended space above the drum, has been designed.[37] The unit is easily loaded and accommodates waste stacked to as high as 5 ft. Rolled-up paper (generated largely during refueling), when placed endwise in the drum, can be compacted with ease. The drum enclosure is equipped with a complete filter system: exhaust fan, air filter, gages, and controls. Filled drums can be removed by overhead crane or lift truck.

Incineration of dry radwastes has not been standard practice at U.S. nuclear power plants, with the possible exception of Yankee-Rowe (as previously mentioned). Because it reduces not only volume but also weight, there has been a growing interest in the use of incinerators for this purpose. For example, the Canadians (Ontario Hydro) have recently purchased an incinerator[42] for their Bruce site and plan to store the drummed ashes in their onsite engineered storage facility.[43] The Canadian unit is not designed to burn wastes contaminated with large amounts of radioactivity (e.g., ion-exchange resins). Future treatment of the

Bruce incinerator ash could include immobilization using any of the solidification agents discussed in this report. Currently, research, development, and demonstration programs are under way at Department of Energy (DOE) installations, at which the feasibility of using incineration[44] on DOE radioactive wastes is being studied.[45,46] Much of the information gained in these studies should be directly applicable to incineration of radwastes generated at nuclear power plants.

6. SOLIDIFICATION AGENTS AND MIXING

The properties that are usually considered of primary importance to the safety and economics of solidified waste management are:

a. low leachability,
b. high thermal conductivity,
c. chemical stability,
d. radiation resistance,
e. mechanical ruggedness,
f. noncorrosiveness to container,
g. minimum volume, and
h. minimum cost.

Low leachability is important in case of an untoward event. Low leachability can reduce the amount of additional treatment, containment, and surveillance that is required. High thermal conductivity increases the amount of activity that can be stored in a container (i.e., increases the permissible volumetric heat generation rate). In the main, it is not a major consideration with the wastes generated at LWRs. Good chemical stability and radiation resistance are necessary if waste forms are to retain their original properties and pressurization of the container by radiolytic gases is to be minimal. Mechanical ruggedness is desirable to reduce the probability of waste products breaking into smaller pieces since such pieces would be more readily dispersed under accident or normal circumstances. Noncorrosiveness to the container is necessary since, in part, it determines the life of the primary container. In most cases, corrosion from the outside should outweigh corrosion from the inside with solidified products. Minimum volume is desirable primarily for economic reasons. Minimum cost, which does not affect product quality, is an obvious advantage.

As the above list of desired properties brings out, solidified waste should be in the form of a nondispersible, free-standing monolith inside the shipping container, and no residual or free liquid (see Glossary, Sect. 10) should be present. An ANSI committee[35] has attempted to specifically define these conditions within the framework of U.S.

Department of Transportation (DOT) regulations. Power plant liquid radwastes can have wide variations in chemical species, some of which may prevent or retard solidification. Thus, a potential exists for free liquid to remain in the container following the solidification step. In view of this, the NRC considered it necessary that designers and operators of solidification systems implement procedures to assure the absence of free liquid. Measures currently acceptable to the NRC[36] are either a Process Control Program or a Free Liquid Detection System, which are described below.

Process Control Program — In the Process Control Program, boundary conditions (in the form of process parameters for the solidification system) will be established such that operation within these limits will give reasonable assurance that solidification is complete. The boundary conditions for each solidification system should be determined by tests with constituents that could be found in the liquid wastes from the nuclear power plant. These boundary conditions will be established as measurable physical parameters which are important to the solidification process such as: chemical content of the liquid waste being solidified (e.g., pH, oil content, etc.), chemical quality of solidification agents (e.g., catalyst pH, type cement, etc.), and liquid waste-to-solidification agent ratios. Once the boundary conditions are fixed, the operator will be expected to stay within these limits since they will be part of the solidification system operating procedures.

Free Liquid Detection System — The Free Liquid Detection System requires a check of each container to verify that free liquid is absent. Visual inspection of the upper surface of the waste product is not alone sufficient to ensure that no free liquid remains in the container. Methods used to verify the absence of free liquid should recognize that some solidification procedures may create a thin, dry layer or crust of solidified material on top, while the waste underneath remains only partially solidified.

The most common radwaste solidification agents used in the United States have been cement and urea-formaldehyde resin. Recently, different types of organic polymers have entered the domestic radwaste service market, and soon asphalt (which has been widely used in Europe for many years) is expected to make its U.S. debut as a commercial radwaste binder. The chemical and physical properties of each of these solidification media and the methods used in their batch and/or continuous process applications are discussed in the following sections.

6.1 Cement

The two methods used for mixing radwaste with cement are in-drum (or in-container) and in-line mixing. These are described following a discussion of the physical and chemical properties of cement.

Portland cement is often used in radwaste solidification processes. The major constituents of portland cement are tricalcium silicate ($3CaO \cdot SiO_2$), dicalcium silicate ($2CaO \cdot SiO_2$), tricalcium aluminate ($3CaO \cdot Al_2O_3$), and tetracalcium alumina ferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$).[47-49] Portland cement is classified as Type I, II, III, IV, or V, depending on the proportions of these compounds in the mixture. Minor constituents such as lime (CaO), magnesia (MgO), or gypsum ($CaSO_4$) can have a significant effect on the swelling and setting properties of the cement. Gypsum is added to prevent flash setting. The American Society for Testing and Materials (ASTM) has defined the restrictions on the chemical composition of portland cements as imposed in all national standard specifications.[50]

Studies on the fundamental chemistry[47-49] of the hardening and setting of portland cement show that upon addition of pure water, both the dicalcium and tricalcium silicates react to form an amorphous, high-strength "rigid gel" or "mineral glue" composed of colloidal tricalcium disilicate hydrate ($3CaO \cdot 2SiO_2 \cdot 3H_2O$) in a nearly homogeneous mass. The tricalcium aluminate and tetracalcium alumina ferrite apparently form the crystalline hexahydrates ($3CaO \cdot Al_2O_3 \cdot 6H_2O$ and $3CaO \cdot Fe_2O_3 \cdot 6H_2O$) indicating a capacity for holding water that is nearly double that of the silicate components. The total amount of water chemically tied in hardened portland cement paste corresponds to approximately 25% by weight. In the initial setting process, a coagulation structure is formed by individual crystallites in the amorphous gel; subsequent hardening proceeds as a fine crystalline network builds within the coagulated framework.

In actual power plant practice, where radwaste solutions and slurries (instead of pure water) are combined with the portland cement, the chemistry of solidification becomes far more complicated and undefinable. Practical experienc however, has shown that although Type I portland cement is the one most commonly available, Type II is preferable in most radwaste applications because it is more resistant to sulfate deterioration. Boric acid wastes are known to retard the setting of portland cement,[51] and some investigations of boric acid and cement mixtures are being carried out at Brookhaven National Laboratory[21-26] and Hanford Engineering Development Laboratory.[52-54] In general, radwaste-cement products with satisfactorily high mechanical strength and low leach rate contain about 5 to 10 wt % waste solids with a rapid decrease in strength reported when the waste solids exceed 10 to 15 wt %. Marked decreases in mechanical strength may also occur when dewatered resins and/or filter sludges are incorporated in cement. Using cement as the solidification agent for liquid radwaste always results in a net volume increase. The final solidified waste volume for radwaste-cement products can be as much as a factor of 2 (or more) greater than the volume of the incorporated liquid. The use of additives such as clays, shales, flyash, or sodium silicate can either enhance or mitigate certain chemical or physical properties of the cementing process. The liquid tolerance of portland cement is increased by sodium silicate addition, thus permitting greater shipping efficiencies (i.e., volume of waste per unit volume shipped), according to ref. 55.

In the early nuclear plants, in-drum mixing was accomplished at BWRs by electrically driven paddle-type mixers or drum rolling, and at PWRs by filling the drums with dry cement intimately mixed with vermiculite prior to introducing the liquid through a header at the top center of the capped drum. The vermiculite served as a medium to disperse the liquid evenly throughout the mix. More recently, a fully automatic in-drum mixing scheme has been developed in which preweighed dry cement and a metal mixing bar are placed in a closed-top 55-gal drum.[56] The drum is then placed behind shielding and remotely filled with waste liquid which has been adjusted to the proper pH, concentration, etc. After being capped remotely, the drum is next placed on an end-over-end tumbler for thorough mixing. A line diagram of the system is given in Fig. 21. The first radwaste solidification system of this type was installed at Salem Nuclear Station.

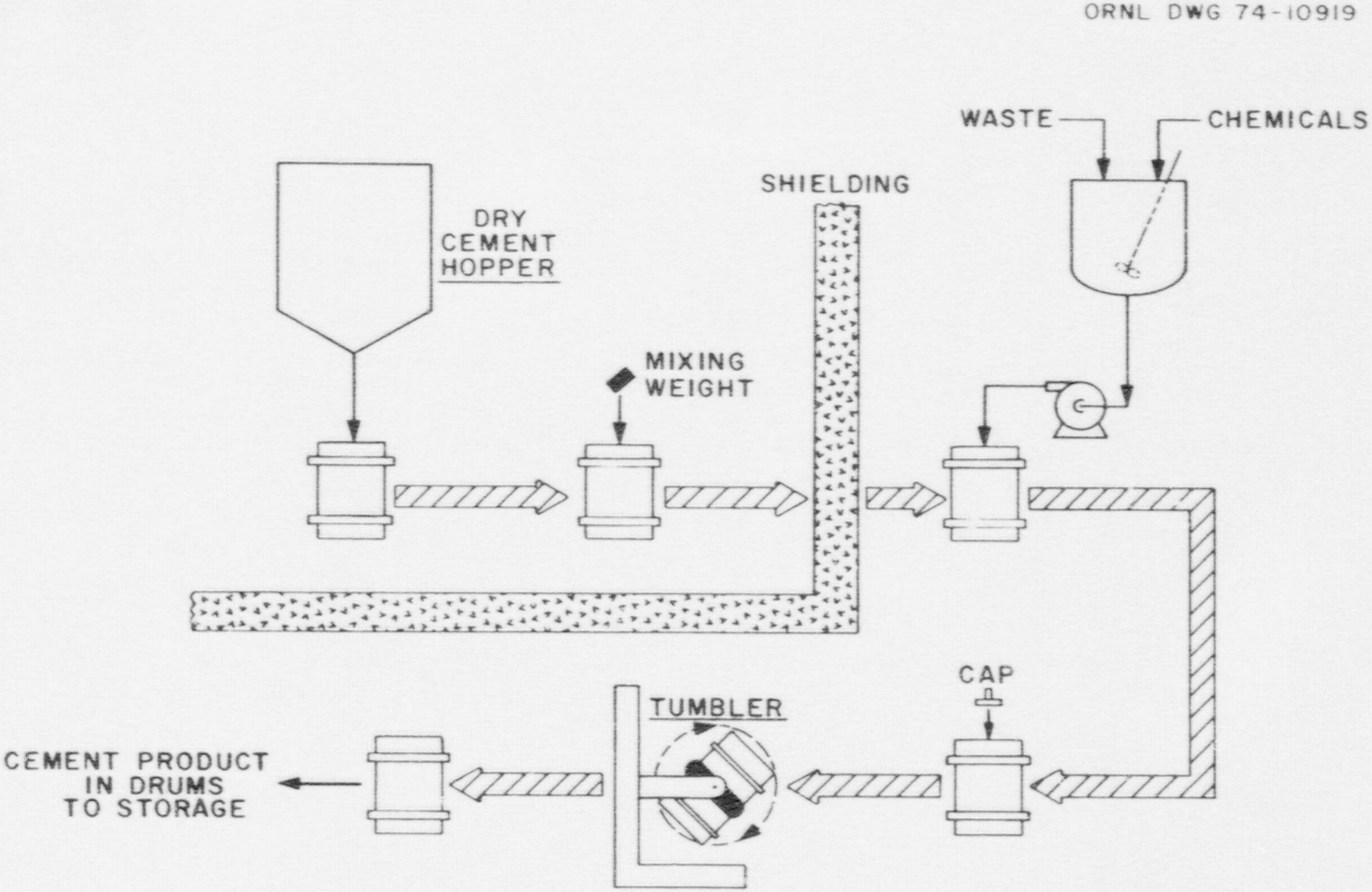

Fig. 21. In-drum mixing process for incorporating radwaste in cement.

In-line mixing can be used to blend liquid radwaste and cement prior to loading the storage drum or container. Advantages frequently cited for in-line mixing are the small holdup volume in and the easy cleaning of the mixer.[57] Various types of in-line mixers are used, including ribbon mixers and open-throat Moyno-type positive displacement pumps. The waste and cement are fed to the mixer at predetermined rates, and the paste (waste plus cement) is discharged from the mixer into the storage container. A typical system, including the option of sodium silicate additive, is shown in Fig. 22.

6.2 Urea-Formaldehyde Resins

The urea-formaldehyde (UF) resins used in radwaste solidification systems are viscous, syrupy, milky-colored materials which are commercially available from a number of suppliers, among them the Borden Chemical Company (Casco-Resin) and the American Cyanamid Company (Cyanaloc). The products have a limited stability or shelf life which ranges from about six months to one year depending upon the temperature. Upon prolonged exposure to air or with addition of an acid catalyst, cross-linking polymerization occurs and a solid is obtained.

When used as a solidification agent for radwaste, the mixture of UF resin and radwaste is adjusted to pH 1-2 by addition of a weak acid or acid salt catalyst such as phosphoric acid (H_3PO_4) or sodium bisulfate ($NaHSO_4$). To minimize the amount of catalyst needed to adjust the pH for highly buffered solutions (e.g., partially neutralized boric acid wastes), dilute solutions of strong acids may be used. Upon addition of the catalyst, a condensation-polymerization reaction occurs which is similar to the reaction that took place during the partial polymerization which was used in preparation of the resin. The reaction is slightly exothermic and is both temperature and pH dependent. The amount of catalyst added controls the setting time. All of the several possible mechanisms for forming the cross-linked UF polymer produce water as an end product of the reaction.[58] The UF polymer formed varies according to reaction conditions but typically has a low molecular weight and an average degree of polymerization of 6-7.[58] The time required for the

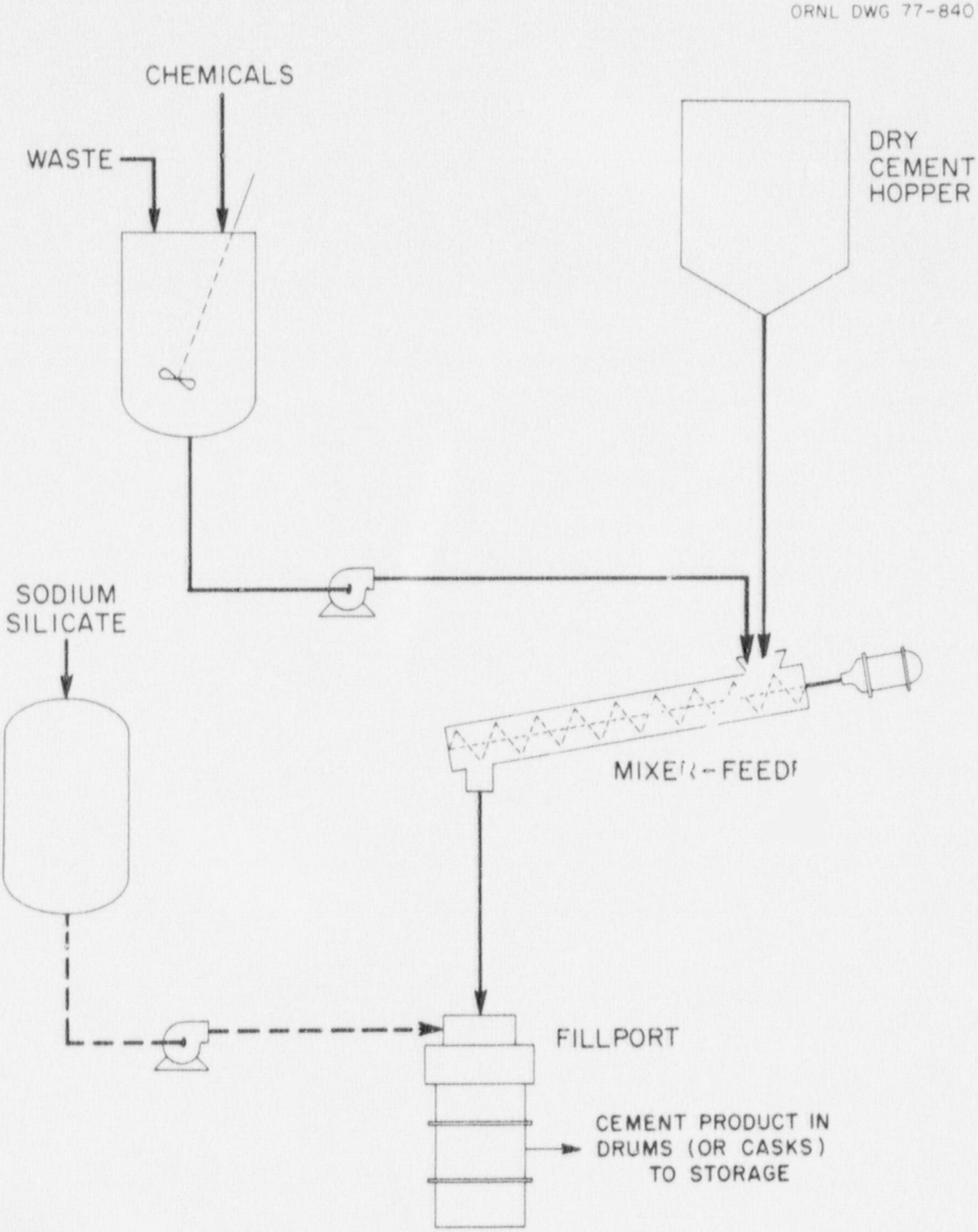

Fig. 22. In-line mixing process for incorporating radwaste in cement.

polymer to reach full strength is shortened by increasing the temperature or increasing the catalyst concentration.

In actual nuclear power plant practice, the volume ratio of evaporator concentrates to UF resin is in the range of 1 to 3 (ref. 59). The amount of catalyst required to reach the desired pH must be determined for each waste and normally comprises about 2 to 3 vol %. After the initial setting, curing to a reasonably hard solid takes place over several hours and sometimes free, slightly acidic water, which can be mildly corrosive to the container, is released in the process.[60] Portland cement [illegible] orbent materials have been added to the waste containers to eliminate such residual water after the mixture has set. Urea-formaldehyde resins are also used to encapsulate radwastes such as dewatered filter sludges and spent demineralizer resins slurried with small quantities of liquid waste. Certain wastes (e.g., soap solutions and concentrated Na_2SO_4) are difficult to incorporate into UF resin. Acceptable sodium sulfate products can be obtained with fresh UF resin by diluting the Na_2SO_4 to less than 10 wt % prior to resin addition or by precipitating the excess sulfate with calcium chloride, according to ref. 55.

Paper pulp or wood flour imparts strength when added to UF resin formulations. Also, many of the same substances that are added to cement (e.g., the various clays given in ref. 61) can also be added to UF resin to make the products less leachable. In general, however, product strength decreases and leachability increases as the ratio of liquid to UF resin increases. On the other hand, UF products exposed to air lose water by evaporation and may become friable if completely dehydrated.

Each of the UF systems now being marketed uses an in-line mixing procedure for combining the UF resin with the radwaste. All are essentially batch processes since the catalyst is added to the resin and waste mixture either in the fillport to the product vessel or in the vessel itself. A stirred-vessel process for incorporating radwaste in UF resin is depicted in Fig. 23. Waste and resin are pumped to the product container through an in-line mixer. Concurrently, the catalyst solution is pumped to the product vessel in which the waste, resin, and catalyst are stirred.

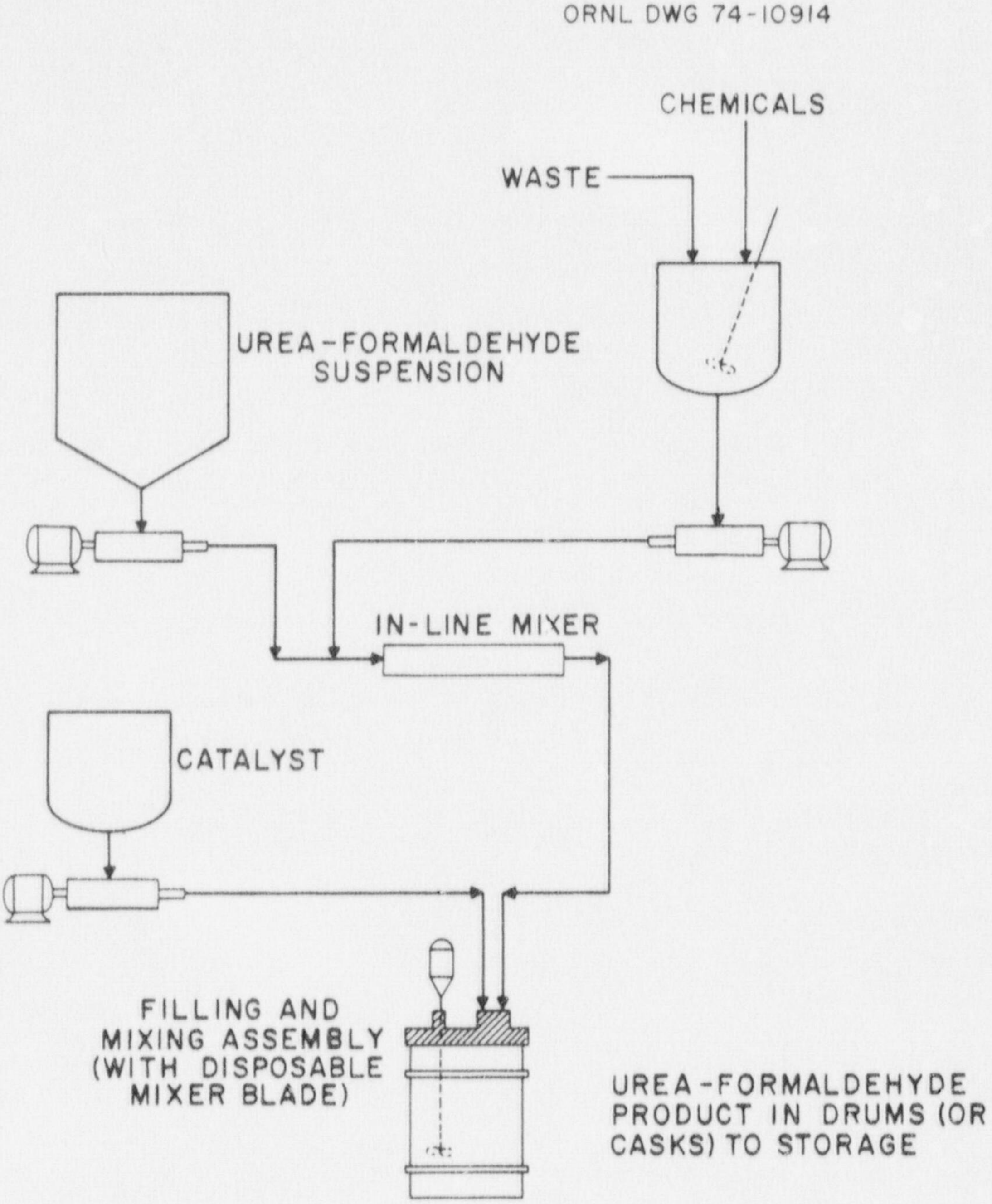

Fig. 23. Stirred-vessel process for incorporating radwaste in urea-formaldehyde resin.

6.3 Modified Vinyl Ester Resins

Several other organic polymers have been examined as media for immobilizing radwastes. Among the polymerized resins, water-extensible polyester (see Sect. 10) or modified vinyl ester resins have been developed.[62-64] The chemistry of these resins is well described in standard texts such as ref. 65.

At present, only one radwaste solidification system using polyester resin is offered commercially.[66] This system, like those using UF resins, encapsulates the waste which is combined with the matrix material prior to addition of a catalyst solution that promotes solidification. However, in the polymerization of polyester resins, water is not produced as it is in the polymerization of UF resins. The waste solutions from the chemical cleaning of Dresden Unit 1 (ref. 67) are scheduled to be solidified using polyester resins.

6.4 Asphalt

Several techniques have been developed and used for incorporating radwaste into asphalt. These include thin-film evaporator[68] and extruder/evaporator[40] processes. Among the thermoplastics, polyethylene has been investigated as a substitute for asphalt.[69]

The term asphalt[70-72] covers mixtures of high-molecular-weight organics with properties related to the aliphatic and aromatic hydrocarbons. Asphalt can be separated by suitable solvents into two fractions or phases: the asphaltenes, which precipitate out as a black tar, and the malthenes, which remain in the solution in the form of a dark, viscous oil. The properties of the fractions obtained depend only on the solvent (usually normal heptane), and there is no sharp boundary between the two phases. The malthenes have the properties of a viscous liquid, while the asphaltenes impart colloidal properties to the asphalt. Asphaltenes show a tendency, in combination with the aromatic fraction of the malthenes, to form complex micelles which are suspended in the malthene phase. If there are sufficient aromatic substances to saturate the absorption capacities of the asphaltenes, the micelles are mobile in the malthene phase, and the colloidal solution is in the sol state. If there are insufficient aromatic substances, the micelles are attracted to each other and form a network. The solution is then in the gel state, giving the asphalt elastic properties. Mechanically, asphalts can behave either as elastic solids or as viscous liquids with intermediate states of behavior also possible.

Asphalts that are used or considered for use in radwaste solidification include straight-run distillation, oxidized (or air-blown), cracked, and emulsified types as described in Sect. 10. Being petroleum derivatives, asphalts are capable of supporting combustion. In general, the properties of asphalts considered most strongly in radwaste applications are penetration, viscosity, and flash point. An oxidized asphalt, widely used for roofing work in the United States, is the one recommended for the commercially available extruder/evaporator.[40]

The earliest processes for incorporating radwaste in asphalt used stirred-batch, electrically heated evaporators.[73] The long residence times and high surface temperatures in these processes caused hardening of the asphalt and distillation of light oils and tars, which make off-gas purification difficult. The processes or systems that have gained favor are those which use a fluid heat transfer medium (e.g., steam) and devices with low holdup volume (e.g., an extruder/evaporator or thin-film evaporator).

6.5 Comparison of Agents

Immobilization of radwastes by incorporation in cement has been practiced for several decades but, despite these years of experience, solidification with cement is not completely understood. Because of the complex chemistry (interactions or lack of interactions between the waste constituents and cement), it is generally conceded that each new application must be considered and tested individually. Solidification with cement and urea-formaldehyde or polyester resins does not require the application of heat as does solidification with asphalt. Obviously, the flammability of organic solidifcation agents (especially at elevated temperatures) is a factor that cannot be ignored when they are used. Speaking broadly, the organics can accommodate a wide range of wastes and waste proportions, whereas cement solidification requires a rather rigid formulation.

A greater accumulation and publication of data on radwaste products (e.g., as typified by refs. 21-26 and 52-54) is needed by the nuclear industry for proper appraisal of solidification systems. Table 1 gives a qualitative comparison of cement, urea-formaldehyde resins, modified vinyl ester resins, and asphalt More of the reported advantages and disadvantages of these solidification agents are presented in refs. 74-76.

Table 1. Comparison of cement, urea-formaldehyde resin, asphalt, and modified vinyl ester resin when used as solidification agents for radwaste at LWR nuclear reactor power plants[a]

Comparison factor	Cement[b]	Urea formaldehyde	Polyester	Asphalt
Shelf life of immobilizing agent	Long	Short (months)	Long	Long
Mix fluidity	Poor	Good	Good	Fair
Mixer cleanability	Poor	Good	Fair	Fair
Chemical tolerances				
Boric acid Sol'n	Poor	Good	Good	Good
Na_2SO_4 Sol'n	Fair	Reduced efficiency	Good	Good
Alkaline Sol'n	Good	Reduced efficiency	Good	Good
Laundry det. Sol'n	Poor	Poor	Fair	Fair
Organic Liquids	Poor	Poor	Fair	Fair
Ion exch. resins	Fair	Good	Good	Fair
Sludges	Good	Good, may require pH adjustment	Good	Good
Volumetric efficiency[c]	Low (0.5)	Moderate (0.6–1.0)	Moderate (0.6–1.0)	High (>2)
Product form	Monolith	Monolith	Monolith	Monolith
Product density, g/cm^3	1.5–2.0	1.0–1.3	1.0–1.3	1.0–1.5
Water binding strength	Good	Fair	Good	Water evap. during preparations
Residual free water	Seldom	Occasionally	Seldom	Never
Mechanical strength	Good	Fair	Good	Good
Product stability	Very good	Fair (loses water and strength in open system)	Good	Good
Combustibility	No	Yes	Yes	Yes
Freeze/thaw resistance	Fair to good	Poor	Unknown	Good
Leach resistance	Moderate to high	Low to moderate	High	Moderate to high

[a] Taken from U.S. ERDA, *Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle*, Vol. 2, "Alternatives for Waste Treatment," p. 12.4, ERDA-76-43 (May 1976), with minor editing and the addition of polyester.

[b] Without additives.

[c] Defined as the ratio of the volume of radwaste treated to the volume of final product.

7. OPERATIONAL EXPERIENCE AT LWRs

The responses to the ORNL questionnaire from 28 of the 62 LWRs (excluding Shippingport) which were in operation at the end of 1976 provided operating data on some solid radwaste handling methods currently in practice. These data, plus information gathered from NSSS vendors, architect-engineers, and suppliers of radwaste treatment equipment and/or services, were compiled and tabulated separately for PWRs and BWRs. The PWR data are presented in Tables A-1a and -1b (Appendix A); the BWR data, in Tables A-2a and -2b.

The streams, operations, and wastes from LWRs differ in detail between PWRs and BWRs, and also among PWRs and among BWRs. Liquid waste streams are treated at reactor sites for the removal of radioactive elements to produce concentrations of radionuclides that are below the limits specified for discharge. The main sources of wastes to be managed from reactor operations are therefore the solids resulting from the cleanup of aqueous streams and from general maintenance operations. The maintenance operations produce mostly a dry trash and also some failed equipment. The wastes from water cleanup consist of solutions or slurries (evaporator concentrates), sludges (filter cakes), filter cartridges, and spent resins. In the future, requirements will necessitate solidification of all these wastes generated in water cleanup. All the types of solid radwaste generated in liquid stream cleanup at each kind of plant, as well as dry compressible wastes, are included in the summary tables, A-1a, -1b, -2a, and -2b, mentioned above.

To date, portland cement, with and without additives, and urea-formaldehyde resins have been the principal solidification agents used in the United States. However, asphalt has been widely used for this purpose in Europe for about two decades and in the near future is expected to be used here. All of these solidification systems have experienced some kind of difficulty in operation; for example, flash hardening has occurred in cement systems, free liquid has occurred in urea-formaldehyde products, and fires have occurred in asphalt systems in European research facilities.

At this time, the main problem areas in radwaste solidification at the power plants appear to be drum capping, monitoring, and decontamination, which remains largely a manual operation; poor performance of sonic level indicators, which are noisy and unreliable; oil contamination in the liquid waste streams, which can interfere with the solidification process in some cases (e.g., cement); free liquid in solidified packages, especially with the urea-formaldehyde solidification agent; and lack of a solidification process control program. To cope with drumming problems, many plants have replaced or modified their original radwaste processing equipment in an effort to perform more of the operations remotely and automatically. Others have contracted with radwaste service vendors to bring their special equipment to the site and do the liquid solidification and/or resin and sludge dewatering operations. These mobile units frequently use a UF solidification agent, although cement with additives such as silicate is also popular. Dewatering resin or sludge involves transferring the slurry from a storage tank into a disposable container inside a truck-mounted shielded cask and removing the water by pumping it out of screened ports in the bottom or wall of the container. The radiation levels of some spent resins and filter cartridges and/or precoat filter sludges can be as high as 100 R/hr or more, and unless adequate shielding is provided during storage, transfer, and packaging, there is risk of high exposure for operating personnel. Several plants indicated that the radwaste area often has the highest radiation background of any place within the plant. To minimize resin handling, some plants are moving toward using disposable ion-exchange units which are discarded in toto. Replies to the questionnaire did not always distinquish between dose rate (e.g., mR/hr) and exposure (e.g., man-rem), which were expressed in several ways (see Table A-1b). Additionally, replies to the questionnaire did not give any information about transuranic elements in process streams and wastes, although some results of measurements for these elements in LWRs are available (e.g., refs. 77 and 78).

The length of time that wastes are stored onsite varied considerably from plant to plant. Some of the smaller, older plants store spent resins, sludges, and filters for several years, whereas many of the newer larger plants tend to keep their onsite inventory of these items to a minimum by frequent packaging followed by almost immediate shipment. At PWRs, spent cartridges are collected in lead or concrete-lined drums or in disposable liners inside shielded shipping casks and may be solidified with evaporator concentrates prior to shipment. Occasionally, HEPA filters are also treated in this manner. At BWRs, resins and/or filter sludges are collected in storage tanks, then transferred to disposable liners inside shielded shipping casks where they are simply dewatered. The BWR plants that do not use this procedure may use either a centrifuge or flat-bed filter to dewater resins and/or sludges before packaging for offsite shipment.

The free-liquid problem took most of the discussion time in the Solidification Workshop held in New Orleans, January 12-14, 1977 (ref. 60). Although free liquid may appear in all the solidification systems (with the exception of asphalt which boils the water away), nearly all the complaints came from users of UF resins. Water is an end product in the polymerization of UF resins, and the amount varies according to the proportions of urea and formaldehyde present. The age of the reagent and the temperature also have an effect. Visual observation of the top surface of the solidifed mass alone is not sufficient proof that no free liquid is present. One plant (Palisades) reported a hard, 6-in.-thick crust on top and "cottage cheese" underneath that yielded 50 gal of free liquid from a total volume of 350 gal when a drain plug at the bottom was opened. Trojan reported a similar experience. The "broomstick method" used in several plants to detect free water was admittedly inadequate, but no one has yet found a more reliable method. The free liquid is slightly acidic and could be somewhat corrosive to the storage container. When there is obvious evidence of free liquid in a storage container, some plants add portland cement to solidify it. At present, process control within certain parameter limits is probably the best method available to assure that there is no free liquid. The newer organic polymers (i.e., modified vinyl ester or water-extensible polyester resins) do not produce water in the polymerization step. Thus, it is claimed that free liquid should not be a problem in these systems.

The incorporation of spent resins into cement requires careful control of the proportions of solid and liquid in the mix to ensure adequate mechanical strength. Incorporation in asphalt requires careful temperature control since resins, especially the anion type, decompose at relatively low temperatures.

The problems encountered with solidification processes have a variety of causes and are not the same for all solidification agents. For example, the setting of cement may be retarded or prevented by the presence of organics such as oils and surface tension depressants. The [illegible] effect of these materials on cement and on organic solidification agents [viz., thermoplastics (e.g., asphalt) and thermosetting resins (e.g., polyester)] needs further study.

The dry wastes at most LWRs are compacted into 55-gal drums for offsite shipment. They are, for the most part, low in radioactivity (i.e., dose rate of a few mR/hr) and are usually stored onsite until enough drums accumulate to comprise a full shipment. The dry fraction of solid waste shipped from reactor plants ranges from less than 10 to greater than 90%. Plants that use ion exchange instead of evaporation for stream cleanup seem to generate a larger proportion of dry waste. The amounts of this type of waste, which includes contaminated papers, rags, clothing, etc., increase significantly during refueling operations. Ventilation filters (HEPAs) often account for a significant portion of the dry waste shipped from a plant. Most plants place the spent air filters in plastic bags and ship them in wooden boxes or crates, but a few plants reported compacting them into drums for shipment.

Nearly all plants use some form of administrative control to minimize the generation of radioactive wastes. Some restrict the use of liquids; others enforce strict control over the movement of unnecessary solid materials into potentially contaminated areas.

Consideration of wastes from large, nonroutine cleanup operations,[67] as well as from the decontamination and decommissioning of retired plants,[79-81] was not within the purview of this study. However, it is recognized that these operations do generate liquid and solid radwastes requiring special treatment.

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10. GLOSSARY

Absorption implies the more or less uniform penetration of a solid by a liquid that is assimilated by the solid (cf. adsorption and sorption).

Adsorption implies that, for the most part, a liquid adheres to the surface of a solid, i.e., the concentration of the liquid is greater at the surface than in the bulk.

Amorphous is a word used to describe a substance in which the distribution of atoms or molecules is not altogether regular, that is, the substance is not crystalline (qv).

Asphalt is a term which covers a brown or black mixture of high-molecular-weight organics related in their nature to the aliphatic and aromatic hydrocarbons.

Backflush describes the operation in which a reverse flow of fluid (air, nitrogen, water, etc.) through the filter medium is used to effect solids removal.

Becquerel (Bq) is a unit used in measuring radioactivity equal to the quantity of any radioactive material in which the number of disintegrations per second is one.

Bitumen is a loosely used word which denotes any of several hard or semi-solid organic materials (native or manufactured) including asphalts, tars, pitches, and waxes.

Blowdown is a term used to denote the liquid and/or solid removed (generally periodically but sometimes continuously) from a vessel or system to prevent excessive solids buildup.

Burial ground signifies an area designated for storing containers of treated radioactive waste by near-surface burial in geologic media (cf. disposal).

Cake is used synonymously with filter cake (qv).

Cement generally denotes portland cement (qv) in radioactive waste treatment terminology unless otherwise specified (e.g., high-alumina cement).

Container is a term applied to the primary vessel (drum, liner, etc.) used to hold and confine solidified radioactive waste.

Cracked asphalts are products obtained by pyrogenic breakdown of heavy petroleum molecules. Temperature fluctuations have a considerable effect on them. They are used mainly in cases where good flow at high temperatures and subsequent rapid hardening on cooling are required. Some properties are: a softening point of 77 to 85°C, a penetration at 25°C of <0.5 mm, and a flow temperature of 150°C.

Crud is a loosely used term that is sometimes employed to represent nondescript, undissolved solids.

Crystalline is a word used to describe a substance that is distinguished by a complete regularity of arrangement of the atoms or molecules of which it is constituted.

Curie (Ci) is a unit used in measuring radioactivity equal to the quantity of any radioactive material in which the number of disintegrations per second is 3.7×10^{10} ($\text{Bq} = 2.7 \times 10^{-11}$ Ci).

Decommissioning describes the preparation of worn-out or obsolete nuclear facilities for retirement. Decommissioning operations remove facilities such as fuel fabrication plants, power plants, and burial grounds from service and reduce or stabilize radioactive contamination. Concepts include: (a) demolition and restoration to original conditions requiring no control, (b) partial demolition and fixation of residues, and (c) minimal demolition followed by isolation and control of residues.

Dewater describes an operation in which water that is not chemically or physically bound (frequently called "excess water") is removed from a radioactive solution or slurry.

Diatomaceous earth (DE) is a natural material formed mainly of the siliceous shells of diatoms (microscopic algae). It is used as a filter medium after being subjected to a refining process that includes crushing, grinding, screening, drying, and calcining. Diatomite is a synonym, as is diatomaceous silica.

Disposal describes operations designed to eliminate wastes from existence on earth or to permanently isolate them from the biosphere with no expectation of retrieval after emplacement. Isolation concepts include: (a) placement in subsurface geologic formations using technologies that offer no practical method for recovery and (b) emplacement into or beneath sea floors. Elimination concepts include extraterrestrial disposal and transmutation.

Dry Wastes consist mainly of ventilation air filters and contaminated clothing, rags, and papers which are normally of low enough radiation level to permit contact collection and manual packaging for on- or off-site storage.

Emulsified asphalts are emulsions of asphalt and water formed by using surface-active agents. Alkaline soaps and amine salts are the agents primarily used for anionic and cationic emulsions respectively. On contact with a prepared surface, the emulsion spreads over it, and as the water evaporates, an asphalt coating is left on the surface.

Encapsulation means to cover on all sides or completely surround a substance with solidification agent (qv).

Evaporation is the removal of liquid from a solution or slurry by vaporization of the liquid.

Filter aids are granular or fibrous materials capable of forming a highly permeable filter cake (qv) on or within which solids from the feed slurry (prefilt) will be trapped.

Filter cake is a term applied to the mass of solids deposited on a filter medium or within a filter aid.

Filter/demineralizer describes a unit that combines filtration and ion exchange using nonregenerable powdered resins.

Filter sludge is an imprecise mixture comprising filter cake (qv) plus any liquid used to clean the filter and transport the cake.

Filtration of a liquid consists of mechanically separating suspended solids from the liquid by passing the mixture through a porous body, which permits the liquid to flow through while retaining the solids on or within itself.

Final storage denotes a storage operation for which (a) no subsequent waste treatment or transportation is anticipated and (b) conversion to disposal, i.e., termination of monitoring and control, is considered possible (cf. disposal).

Free liquid is a term used to designate liquid associated with a solidified waste that is neither chemically nor physically bound by the solid matrix.

HEPA filter stands for high efficiency particulate air filter.

Heterogeneous waste solid connotes a solidified waste product in which the waste is not uniformly distributed throughout the solid matrix.

High-level waste is a term frequently used to denote (a) high-level liquid waste (qv), (b) the products from solidification of high-level liquid waste, or (c) spent (irradiated) fuel elements which are to be disposed of without reprocessing (i.e., without separating uranium and plutonium from fission products).

High-level liquid waste is a liquid waste stream arising from the reprocessing of spent fuels which contains essentially all the nonvolatile fission products from the fuel.

Homogeneous waste solid connotes a solidified waste product in which the waste is uniformly distributed throughout the solid matrix.

Immobilization designates the treatment of wastes in such a manner as to minimize or eliminate characteristics of fluidity and to impede their movement.

Interim storage is used to depict a storage operation for which monitoring and controls are provided with expectation of subsequent treatment and transportation to final disposition.

Intermediate-level waste is a loosely used term which describes wastes contaminated with beta-gamma activity and requiring more than minimal biological shielding (cf. low-level and high-level waste).

Intermediate-lived nuclide signifies a radioactive isotope with a half-life greater than about eight days but less than about 30 years (cf. short-lived and long-lived nuclide).

Ion exchange is a process in which a reversible stoichiometric interchange of ions of the same charge (sign) takes place between an electrolyte solution and an insoluble solid (ion exchanger).

Liner is a word used to depict a disposable waste container that fits inside a reusable shielded shipping cask.

Long-lived nuclide signifies a radioactive isotope with a half-life greater than about 30 years.

Low-level waste is a loosely used term which describes wastes contaminated with beta-gamma activity and requiring no or minimal biological shielding (cf. intermediate-level and high-level waste).

Micro-Cel is a synthetic, hydrated calcium silicate which as a fine powder is used as a filter aid (qv) or a water-sorbent material.

Other than high-level waste is a phrase denoting intermediate- or low-level waste (qv).

Overpack is a word which describes secondary (or additional) external containment for packaged waste.

Oxidized (or air-blown) asphalts are highly colloidal products formed by blowing air through certain petroleums. Temperature fluctuations usually have little effect on them. Some properties are: a softening point of 70 to 140°C, a penetration at 25°C of 0.7 to 4.5 mm, a density at 25°C of 1.02 to 1.04 g/cm^3, and a flash point of 250 to 290°C.

Particle is a word used to refer to the individual physical unit describing the state of subdivision of matter.

Particulate is a word used synonymously with particle (qv).

Portland cement is a hydraulic (setting or hardening under water) cement made by finely pulverizing the clinker produced by calcining to incipient fusion a mixture of argillaceous (containing clay or clay minerals) and calcareous (containing calcium carbonate) materials.

Primary waste indicates the as-generated form and quantity of a waste.

Rad is a unit used in measuring absorbed radiation dose and is defined as 100 ergs per gram of material.

Receptacle is a word sometimes used synonymously with container (qv).

Repository denotes a facility or location containing wastes in storage or disposal.

Roentgen (R) is a unit of X- or gamma-radiation exposure defined in relationship to the coulomb (C) as $1R = 2.58 \times 10^{-4}$ C/kg air.

Secondary waste includes the form and quantity of <u>all</u> wastes that result from applying waste treatment technologies to a primary waste.

Short-lived nuclide signifies a radioactive isotope with a half-life less than about eight days.

Silver zeolites are cation exchangers with a regular crystal lattice that are produced by crystallization from solutions containing alkali silicate and aluminate at high temperatures and by subsequent replacement of the alkali metal with silver. They are used to remove iodine from gaseous streams since they are capable of combining with both inorganic and organic iodine species, have a high affinity for iodine, and are stable at relatively high temperatures.

Slurry waste is a term applied to liquid radioactive waste with a high content of insoluble solids (>0.1% by wt).

Solidification is taken to mean the conversion of a waste to a dry, monolithic, chemically and physically stable solid.

Solidification agent describes a material which, when mixed in prescribed proportions with a waste solution or slurry, can form a free-standing product with no free liquid.

Solidified waste denotes the solid product obtained by mixing a solution or slurry with a solidification agent. The product is expected to be monolithic with a definite volume and shape and bounded by a stable surface of distinct outline on all sides (free-standing).

Solka-Floc is a cellulosic filter aid.

Sorption is a noncommittal term covering both absorption and adsorption.

Straight-run distillation asphalts are the residues obtained from refining of heavy petroleums. Some properties are: a softening point of 34 to 65°C, a penetration at 25°C of 2 to 22 mm, a density at 25°C of 1.0 to 1.1 g/cm^3, a loss of weight on heating of <2%, a flash point of >230 to 250°C, and an elasticity at 25°C of <100 to >25 mm.

Transuranic elements are elements beyond uranium in the periodic table (i.e., those with atomic number greater than 92).

Transuranic waste is any waste material measured or assumed to contain more than a specified concentration of long-lived transuranic elements. This concentration has not been resolved but is considered by many to be greater than ten nanocuries per gram.

Urea-formaldehyde resin is formed by reacting urea [$(NH_2)_2CO$] with formaldehyde (HCHO) under alkaline or neutral conditions to produce a water-soluble mixture of monomethylol urea ($NH_2 \cdot CO \cdot NH \cdot CH_2OH$) and dimethylol urea ($CH_2OH \cdot NH \cdot CO \cdot NH \cdot CH_2OH$). The final composition of the mixture depends upon the initial ratio of urea to formaldehyde reacting and the conditions of the reaction. The monomethylol and dimethylol ureas are then partially polymerized by a condensation mechanism under slightly acidic conditions followed by neutralization to pH 7-8 to terminate the reaction. The resulting white, highly viscous product is the UF resin which typically contains 60 to 65 wt % solids.

Vermiculite can be any of a number of micaceous minerals that are hydrous silicates usually derived from expansion of the granules of mica at high temperatures to give a lightweight, highly water-sorbent material.

Water-extensible polyester is prepared by condensation of glycols (e.g., ethylene glycol) with dibasic acids (e.g., dicarboxylic acid). The polyester is dissolved in a polymerizable monomer, usually styrene, to form a liquid into which waste solutions or slurries can be dispersed as small droplets. The gelling and curing of the resin phase to form a hard polymer which encapsulates the waste droplets are achieved by initiating the polymerization of the styrene monomer by a suitable catalyst system.

Wet wastes consist mainly of spent ion-exchange resins, sludges from filter- and resin-cleaning operations, and evaporator and reverse-osmosis concentrates, all of which derive primarily from water treatment or purification of liquid streams.

APPENDIX A. SOLID RADWASTE OPERATING DATA FOR LWR NUCLEAR POWER PLANTS IN OPERATION AS OF DECEMBER 31, 1977

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Table A-1a. Methods of treatment used for preparing wet and dry radioactive wastes for offsite shipment from pressurized water reactors[a]

Installation	Wet waste		Solidification system	Dry waste		
	Type of waste[b] generated	Type of waste[b] solidified		Percent of total solid waste compacted	Compaction volume reduction factor	Average mass per drum (lb)
Yankee-Rowe	CF, BR, EB	EB	Manual (cement) for evaporator bottoms: commercial vendor dewaters and ships resins; spent cartridges shipped in cement-lined drums	0[c]	0[c]	*c*
Indian Point	*a*	*a*	Hittman (UF) for liquids	*a*	*a*	*a*
San Onofre	CF, BR	None	Manual packaging; spent cartridges shipped in cement-lined drums; no solidification equipment	60[d]	6	Not determined
Connecticut Yankee	*a*	*a*	*a*	*a*	*a*	*a*
Ginna	*a*	*a*	*a*	*a*	*a*	*a*
Robinson	*a*	*a*	*a*	*a*	*a*	*a*
Point Beach	*a*	*a*	ATCOR (cement)	*a*	*a*	*a*
Palisades	CF, BR, EB	EB	PPI (UF) in 50-ft^3 liners for evaporator bottoms; resins dewatered in 100-ft^3 liners in shipping cask; spent cartridges collected in 100-ft^3 liner until full	7	*a*	250
Surry	*a*	*a*	*a*	*a*	*a*	*a*
Turkey Point	CF, BR, EB	CF, EB	ATCOR (cement) for evaporator bottoms and spent cartridges in 150-ft^3 liners; resins dewatered in shipping cask	22–25	*a*	200–300[e]
Maine Yankee	CF, BR, EB	EB	Hittman (UF) for evaporator bottoms; Hittman shipping cask for dewatering resins	60,000 lb in 1976	*a*	*a*
Oconee	CF, BR, EB	EB[a]	Treatment of evaporator bottoms not reported; spent cartridges are collected in liner within a reusable shield and so are spent resins	*a*	*a*	300
Zion	CF, BR, EB	CF, BR, EB	Envirogenics (cement-vermiculite) for evaporator bottoms, spent resins, and some cartridge filters. Manual except for drum filling	0[f]	no compactor	*f*

Table A-1a (continued)

Installation	Wet waste		Solidification system	Dry waste		
	Type of waste[b] generated	Type of waste[b] solidified		Percent of total solid waste compacted	Compaction volume reduction factor	Average mass per drum (lb)
Fort Calhoun	CF, BR, EB	BR, EB	Manual (cement-vermiculite mixture + lime) for evaporator bottoms and spent resins. Resins and spent cartridge filters stored in concrete or lead-lined drums. ATCOR (cement) solidification system is planned	10	10	~200
Prairie Island	*a*	*a*	ATCOR (cement)	*a*	*a*	*a*
Three Mile Island	CF, BR, PR, EB	CF, BR, PR, EB	PPI (UF) in 50-ft^3 liners for evaporator bottoms, powdered resin filter sludges, spent cartridge filters, and ion-exchange resins	25	*a*	150
Kewaunee	CF, BR	CF, BR	ATCOR (cement) for spent cartridge filters and resins; cartridges stored in drums with concrete liner, precast at the site, and when drum is full, dry cement is added to take up moisture prior to final capping with precast concrete cover under the steel drum lid	75	*a*	250–300 (dry waste); 500 (cartridge filters); 700–800 (solidifie resins)
Arkansas One	*a*	*a*	PPI (UF)	*a*	*a*	*a*
Rancho Seco	*a*	*a*	Nuclear Waste Systems (cement)	*a*	*a*	*a*
Calvert Cliffs	*a*	*a*	Hittman (cement)	*a*	*a*	*a*
Cook	CF, BR, EB	EB	Hittman (UF) mobile unit for solidifying evaporator bottoms in 1500-gal steel tank for shipment (cement-vermiculite added to solidify any visual surface water); spent cartridges stored in 50- and 30-gal drums prior to shipment in a shielded cask; spent resins are stored in tank, and none have been shipped to date	40	*a*	300

Table A-1a (continued)

Installation	Wet waste		Solidification system	Dry waste		
	Type of waste[b] generated	Type of waste[b] solidified		Percent of total solid waste compacted	Compaction volume reduction factor	Average mass per drum (lb)
Millstone 2	*a*	*a*	UNI & PPI (secondary) (UF)	*a*	*a*	*a*
Trojan	*a*	*a*	PPI (UF)	*a*	*a*	*a*
St. Lucie	CF, BR	None	No solidification equipment; spent resin is dewatered in shipping cask liner; spent cartridge filters are stored and shipped in drums in shielded casks	90–95	*a*	~280
Beaver Valley	CF, BR, EB	CF, BR, EB	ATCOR (cement) system for solidifying evaporator bottoms, spent cartridge filters, and resins in 50-ft^3 liners	80	~1.5–3	90–250
Salem	*a*	*a*	Stock (cement)	*a*	*a*	*a*
Crystal River	CF, BR, EB	BR, EB	Gilbert Associates designed solidification system (cement-sodium silicate-vermiculite) for evaporator bottoms and spent resins. Until it is completely operational, Chem-Nuclear mobile unit (UF) is used to solidify evaporator bottoms; resins are dewatered in shipping cask, and spent cartridges stored in drums are shipped in shielded casks	~25	~5	250–300
Davis-Besse	*a*	*a*	PPI (UF)	*a*	*a*	*a*
Farley	*a*	*a*	*a*	*a*	*a*	*a*
North Anna	*a*	*a*	PPI (UF)	*a*	*a*	*a*

[a] Not reported, not available, or not applicable.

[b] CF = cartridge filters; BR = bead resin; PR = powdered resin; EB = evaporator bottoms.

[c] Except during refueling, dry combustibles are incinerated. The remaining dry wastes represent about 10% of the volume of waste shipped offsite. They are usually packaged in 2.8-m^3 boxes with average filled weight of ~½ ton.

[d] An additional 30% of the solid waste is dry uncompacted waste shipped in wooden boxes.

[e] Other dry waste is packed in 12-m^3 wooden boxes with average weight of ~5 tons.

[f] Zion uses 3.62-m^3 wooden boxes to ship dry wastes which amount to ~2% of the total solid waste shipped.

Table A-1b. Average dose rates and exposures incurred in packaging an[illegible]ing various types of radioactive wastes, the principal isotopes measured, usual onsite inventories and storage times, and the annual volume expected from pressurized water reactors[a]

Installation	Waste type	Principal isotopes	Average dose rate (R/hr)		Typical packaging time requirements (man hours)	Average annual exposure (man-rem)	Usual storage time onsite (days)	Average onsite inventory	Representative specific activity (Ci/ft^3)	Expected annual volume (ft^3)
			Packaging	Shipment						
Yankee-Rowe	Dry	$^{58,60}Co$, ^{54}Mn	0.024^b	≤0.024	*a*	~2.5	90	~40 drums (mostly bottoms)	*a*	~3,500
	Bottoms	$^{58,60}Co$, $^{134,137}Cs$, ^{54}Mn			*a*		40–45		*a*	
	Resin	^{60}Co, $^{134,137}Cs$	*a*	*a*	*a*		2½–3	*c*	*a*	40–45
	Filters	$^{57,58,60}Co$, ^{54}Mn	≤12^c	0.1–0.15	*a*		<30^d	*d*	*a*	4–5
Indian Point	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
San Onofre	Dry	$^{58,60}Co$, ^{134}Cs	*a*	*a*	*a*	~8 (estimated)	30–150	50–100 drums plus 1–4 boxes (168 ft^3 each)	*a*	*a*
	Resin	$^{58,60}Co$, ^{54}Mn, $^{134,137}Cs$	2–100^e	*a*	*a*		≤365^f	None in shipping casks	*a*	<550
	Filters	$^{58,60}Co$, ^{54}Mn	*a*	0.01–0.50	*a*		30–150	*a*	*a*	*a*
Connecticut Yankee	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Ginna	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Robinson	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Point Beach	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Palisades	Dry	$^{58,60}Co$, ^{137}Cs	*a*	50% decayed	*a*	*a*	90	*a*	0.00043	*a*
	Bottoms	Same as above	*a*	0.02	*a*		~14	50-ft^3 liner shipped when full	*a*	*a*
	Resin	Same as above	0.01–100^e	*a*	*a*		~14	100-ft^3 liner shipped when full	*a*	~400
	Filters	Same as above	0.01–100^e	0.005–50^e	*a*		90	100-ft^3 liner shipped when full	*a*	*a*
Surry	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*

Table A-1b (continued)

Installation	Waste type	Principal isotopes	Average dose rate (R/hr)		Typical packaging time requirements (man hours)	Average annual exposure (man-rem)	Usual storage time onsite (days)	Average onsite inventory	Representative specific activity (Ci/ft^3)	Expected annual volume (ft^3)
			Packaging	Shipment						
Turkey Point	Dry	^{58,60}Co, ^{54}Mn, ^{137}Cs	*a*	<0.200	*a*	*a*	*a*	<2,000 ft^3	*a*	*a*
	Bottoms Filters	^{58,60}Co, ^{54}Mn, ^{59}Fe, ^{124,125}Sb, ^{137}Cs	0.05–10[e]	*a*	*a*	*g*	10–45	150-ft^3 liner (bottoms and filters combined)	*a*	~800
	Resin	Same as above	1–100[e]	*a*			<3	80-ft^3 liners shipped when full	*a*	*a*
Maine Yankee	Dry	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	60,000 lb
	Bottoms	*h*	*h*	*h*	*h*	*h*	*h*	*h*	*a*	*h*
	Resin									180[i]
	Filters	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Zion	Dry	*a*	*a*	*a*	*a*	8.3[j]	For drums >1 R/hr, up to 150	*a*	<0.00008	*a*
	Bottoms	*a*	>0.001–10[e]	0.15–0.100	*a*			*a*	*a*	*a*
	Resin	*a*			*a*			*a*	*a*	2,132
	Filters	*a*	*a*	*a*	*a*			*a*	*a*	*a*
Oconee	Dry	*a*	*a*	*a*	*a*		*a*	*a*	*a*	*a*
	Bottoms	Co, Mn	*a*	0.100	*a*	*k*	*a*	8 disposable containers	*a*	*a*
	Resin	Co, Mn	10–50[e]	0.–0.005	*a*		*a*	*a*	*a*	340[l]
	Filters	Co, Mn	40–70[e]	0.–0.005	*a*		<7	1 container shipped when full	*a*	*a*
Fort Calhoun	Dry	^{58,60}Co, ^{134,137}Cs, ^{54}Mn	0.1	*a*	*a*	*m*	7	*a*	*a*	4,250
	Bottoms	Same as above	0.06–0.6[e]	0.1–1.0	*a*		14	30 drums	*a*	*a*
	Resin		None to date		*a*		None shipped to date	None shipped to date	*a*	150
	Filters		0.3–5[e]		*a*		30	2 drums	*a*	*a*

Table A-1b (continued)

Installation	Waste type	Principal isotopes	Average dose rate (R/hr)		Typical packaging time requirements (man hours)	Average annual exposure (man-rem)	Usual storage time onsite (days)	Average onsite inventory	Representative specific activity (Ci/ft^3)	Expected annual volume (ft^3)
			Packaging	Shipment						
Prairie Island	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Three Mile Island	Dry	[a]	[a]	[a]	[a]	[a]	30	35 drums	[a]	[a]
	Bottoms	[a]	0.2	[a]	[a]	[a]	14	50-ft^3 liner shipped when full	[a]	[a]
	Resin	[a]	[a]	[a]	[a]	[a]	None shipped to date	None shipped to date	[a]	[a]
	Filters	[a]	[a]	[a]	[a]	[a]	14–30	[a]	[a]	[a]
Kewaunee	Dry	^{60}Co, ^{54}Mn	[a]	[a]	[a]	[a]	150	Up to 75 drums	0.002–0.003	~1,100
	Resin	^{58,60}Co, ^{134,137}Cs, ^{54}Mn	[a]	>0.05[n]	[a]	[a]	~365	[a]	[a]	~270
	Filters	Same as above	[a]	>0.05[n]	[a]	[a]	~365	[a]	[a]	[a]
Arkansas One	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Rancho Seco	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Calvert Cliffs	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Cook	Dry	^{58,60}Co	0.0003	0.0002	[a]	[o]	60–90	35–75	[a]	6,000
	Bottoms	^{58,60}Co, ^{134,137}Cs, ^{54}Mn, ^{131}I	0.006	[a]	[a]		~1	Accumulate 1,500–4,500 gal	[a]	[a]
	Resin		[a]	[a]	[a]		None shipped	Accumulate ~200 ft^3	[a]	[a]
	Filters		1.85	[a]	[a]		~1	Accumulate ~30 to 35	[a]	[a]
Millstone 2	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Trojan	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
St. Lucie	Dry	^{58,60}Co, ^{54}Mn, ^{137}Cs, ^{90}Sr,	0–0.057	0.015	[a]	[p]	60–90	50–100 drums	[a]	[a]
	Resin	^{57,58,60}Co, ^{54}Mn, ^{51}Cr	40[e]	0.2	[a]		2–30	[a]	[a]	~216
	Filters	^{59}Fe, ^{95}Zr, Nb ^{124}Sb, ^{137}Cs	40	0.2	[a]			[a]	[a]	[a]

Table A-1b (continued)

Installation	Waste type	Principal isotopes	Average dose rate (R/hr)		Typical packaging time requirements (man hours)	Average annual exposure (man-rem)	Usual storage time onsite (days)	Average onsite inventory	Representative specific activity (Ci/ft^3)	Expected annual volume (ft^3)
			Packaging	Shipment						
Beaver Valley	Dry		*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
	Bottoms	^{58,60}Co	*a*	<0.001–0.04	*a*	*a*	*a*	5 50-ft^3 liners	*a*	*a*
	Resin		*a*		*a*		*a*	*a*	*a*	*a*
	Filters		*a*		*a*		*a*	*a*	*a*	*a*
Salem	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Crystal River	Dry	^{58,60}Co, ^{59}Fe	0.1	0.05–0.075	*a*	12,000	90	25–50 drums	*a*	~2,740
	Bottoms	Same as above	0.1–0.3	0.1–0.15	*a*		90	200 drums maximum	*a*	*a*
	Resin		0.07–0.1	0.1–0.15	*a*		1	Dewater and ship	*a*	*a*
	Filters		75–100[e]	0.1–0.15	*a*		*a*	2 drums	*a*	*a*

[a] Not reported, not available, or not applicable.
[b] 0.001–0.005 at beginning of core life and 0.15–0.2 toward end of life.
[c] Handle resins about once every 5–6 years. There were only two shipments in 16 years.
[d] Spent cartridges may be 12 R/hr at contact but are placed in concrete-lined drums for storage; handle filters about twice a year.
[e] Unshielded at contact.
[f] Shipped approximately once per year; stored in spent resin storage tank and contractor does the packaging.
[g] Average dose rate to personnel is <10 mR/hr due to remote, automatic handling.
[h] Maine Yankee has installed a new solidification system since the ORNL questionnaire was answered, thus making the reported operating data obsolete.
[i] Total volume generated during 4.5 years operation.
[j] For 1975.
[k] Reported as 10 mR/day/man.
[l] Total through 1976.
[m] Dose rate 60–100 mR/hr.
[n] Reported as usually requiring Yellow III label.
[o] Reported as 50 mR/man/year.
[p] Reported as 30–50 mR/man/day.

Table A-2a. Methods of treatment used for preparing wet and dry radioactive wastes for offsite shipment from boiling water reactors[a]

Installation	Wet wastes		Solidification system	Dry Wastes		
	Type of waste[b] generated	Type of waste[b] solidified		Percent of total solid waste compacted	Compaction volume reduction factor	Average mass per drum (lb)
Dresden 1	BR[c]	BR[d,e]	No solidification equipment[f]	*a*	*a*	*a*
Dresden 2 and 3	BR, PR, DE, EB	BR, PR, DE, EB	Stock (cement)	*a*	*a*	*a*
LaCrosse	BR[c]	None	No solidification equipment	~80	3–4	100–200
Big Rock Point	BR[c,d]	*a*	No solidification equipment	*a*	*a*	*a*
Humboldt Bay	BR,[d] EB[d]	*a*	Have reported solidified waste since 1973; solidification method not reported	0	No compactor	*a*
Oyster Creek	BR, PR, SF, DE, EB	EB	Hittman (UF)	*a*	*a*	*a*
Nine Mile Point	BR, PR, SF, DE, EB	PR, DE, EB	Hittman (UF) for liquids; cement plus vermiculite for topping dewatered sludge	72	8	164
Millstone 1	BR, SF, DE, EB	EB	UNI (UF)	*a*	*a*	*a*
Monticello	PR, SF, BR[c]	PR, SF, BR	Chem-Nuclear;[g] ATCOR (cement) being revised	50	*a*	*a*
Quad-Cities	PR, BR[c]	PR, DE	PPI (UF)	*a*	*a*	*a*
Vermont Yankee	PR, BR[c]	None	No solidification equipment	54	10	480 (including cement shield)
Pilgrim	PR, BR, DE	None	Chem-Nuclear;[h] ATCOR (cement) not in use	*a*	*a*	*a*
Browns Ferry	PR, BR,[c] EB[i]	EB[i]	PPI (UF) for floor drains	25	5	300
Peach Bottom	PR, BR[c]	None	No solidification equipment	50	6	~200

Table A-2a (continued)

Installation	Wet wastes		Solidification system	Dry Wastes		
	Type of waste[b] generated	Type of waste[b] solidified		Percent of total solid waste compacted	Compaction volume reduction factor	Average mass per drum (lb)
Cooper	PR, BR,[c] EB	EB	UNI (cement) for floor drains	[a]	[a]	[a]
Duane Arnold	PR, BR[c]	[a]	Hittman (UF) for liquids	[a]	[a]	[a]
Hatch	BR, EB	EB	PPI (UF) for regeneration solution wastes	[j]	[a]	[a]
Brunswick	BR, PR, EB	BR,[k] PR,[k] EB	Chem-Nuclear[e,g] (UF)	10	4	[a]
FitzPatrick	BR, DE, EB	EB	[a]	[a]	[a]	[a]

[a] Not reported, not available, or not applicable.

[b] PR = powdered resin; BR = bead resin; SF = Solka-Floc; DE = diatomaceous earth; EB = evaporator bottoms.

[c] Not regenerated.

[d] Stored in onsite tank.

[e] Periodically shipped to burial ground by commercial vendor.

[f] Dow solidification system to be used for decontamination wastes.

[g] Mobile unit, solidification agent is UF.

[h] Mobile unit for dewatering resins but not solidifying them.

[i] Waste evaporator to be installed.

[j] Majority of dry waste is shipped in boxes in noncompacted form.

[k] Dewatered resins not always solidified.

Table A-2b. Average dose rates and exposures incurred in packaging and handling various types of radioactive wastes, the principal isotopes measured, usual onsite inventories and storage times, and the annual volume expected from boiling water reactors[a]

Installation	Waste type	Principal isotopes	Average dose rate (R/hr)		Typical packaging time requirements (man hours)	Average annual exposure (man-rem)	Usual storage time onsite (days)	Average onsite inventory	Representative specific activity (Ci/ft^3)	Expected annual volume (ft^3)
			Packaging	Shipment						
Dresden	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Big Rock Pt.	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Humboldt Bay	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
LaCrosse	Dry	*a*	0.0001–1	0.013	*a*	*a*	1–365	<70 drums	*a*	*a*
	Resin	^{58,60}Co, ^{134,137}Cs, ^{54}Mn	<100	<100	*a*	0.5–0.6	14	<1 tank	0.3	~150 ft^3
	Filter	Same as above	3–6	0.5–5	*a*	1–2	*a*	*a, b*	*a*	*a*
Oyster Creek	Dry	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
	Resin	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
	Filter sludge	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Nine Mile Point	Dry	^{58,60}Co, ^{134,137}Cs, ^{54}Mn	0.008	*a*	*a*		30–60	<100 drums	*a*	*a*
	Bottoms	^{60}Co, ^{134,137}Cs	0.002	*a*	4[c]–6[d]	0.01[c]–0.12[d]	<1	0	~0.05 (9.69 Ci/ 200 ft^3)	*a*
	Resin	^{58,60}Co, ^{134,137}Cs, ^{54}Mn	0.023	*a*	9[d]	0.10[c]–0.30[d]	<1	0	~2.7 (218 Ci/ 80 ft^3)	644
	Filter sludge	^{58,60}Co, ^{134,137}Cs, ^{51}Cr, ^{59}Fe	1.5–7	*a*	64[d]	0.15[c]–0.80[d]	30–60	<100 drums[e]	~0.14 (28.7 Ci/ 200 ft^3)	1,529
Millstone 1	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Monticello	Dry	^{134,137}Cs	0.001–0.1	0.001–0.02	*a*		Few weeks	*a*	*a*	*a*
	Resin[f]	^{134,137}Cs	1–2	0.01	*a*	(0.01–1.0)[d]	Soon after loading	*a*	0.5–1[e]	~3,000
	Filter sludge[g]	^{60}Co, ^{134,137}Cs	2–10	0.015	*a*			*a*		
Quad-Cities	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Vermont Yankee	Dry	^{57,58,60}Co ^{54}Mn, ^{51}Cr, ^{59}Fe	*a*	*a*	*a*	4[h]	90	~140 drums	0.008 (60 mCi/ drum)	4,200–4,500
	Resin[f]	Same as above	*a*	0.05	*a*	<1	7	1 cask	0.001 (170 mCi/ 150 ft^3)	~250
	Filter sludge	Same as above	*a*	0.05	*a*	<1	7	1 cask		~3,350
Pilgrim	Dry	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
	Resin[f]	*a*	<60	*a*	*a*	*a*	*a*	*a*	*c*	>2,700
	Filter sludge	*a*	*a*	*a*	*a*	*a*	*a*	*a*	~28.3 (1000 μCi/1 cc)	144

Table A-2b (continued)

Installation	Waste type	Principal isotopes	Average dose rate (R/hr)		Typical packaging time requirements (man hours)	Average annual exposure (man-rem)	Usual storage time onsite (days)	Average onsite inventory	Representative specific activity (Ci/ft^3)	Expected annual volume (ft^3)
			Packaging	Shipment						
Browns Ferry	Dry	Mixed activation and fission products	*a*	0.0001	*a*	*a*	7	50 drums	*a*	*a*
	HEPAs	*a*	*a*	0.0002	*a*	*a*	14	10 boxes	*a*	*a*
	Resin[f]	Mixed activation and fission products	0.100	0.001	*a*	*a*	0	0	*a*	15,600
	Filter sludge[g]	Same as above	0.350	0.0003	*a*	*a*	0	0		
Peach Bottom	Dry	*a*	0.005	*a*	*a*	<2 per quarter	Variable	*a*	*a*	*a*
	Resin	*a*	<50	*a*	*a*			*a*	*a*	530
	Filter sludge	*a*	<0.2	*a*	*a*			*a*	*a*	20,000
Cooper	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Duane Arnold	Dry	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a* (Majority not compacted)
	Resin Filter sludge	^{58,60}Co, ^{54}Mn, ^{51}Cr	0.05–0.30	*a*	*a*	<1[d]	*a*	*a*	*a*	6750 (Includes 480-ft^3 resins)
Hatch	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Brunswick	Dry	*a*	*a*	*a*	*a*	*a*	30	15–80	*a*	Estimated ~5,000–6,000
	Bottoms	^{58,60}Co, ^{54}Mn, ^{51}Cr ^{59}Fe, ^{131}I, ^{137}Cs	0.1–0.15	*a*	*a*	*a*	<1	*a*	*a*	Estimated ~1,200–1,800
	Resin[f]	Same as above	0.1–0.2	*a*	*a*	*a*	<1	*a*	*a*	<150
	Filter sludge[g]	Same as above	5–25	*a*	*a*	*a*	<1	*a*	*a*	14,600 (40 ft^3/day)
FitzPatrick	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*

[a] Not reported

[b] Four to six shielded drums (30 gal inside 55 gal with concrete in the annulus) have been onsite for 4–5 years.

[c] Supervisory radiation protection personnel on per shipment basis.

[d] Operators on per shipment basis.

[e] Cartridge filters and filter sludges are also packaged in drums.

[f] Condensate demineralizer resins.

[g] Reactor water cleanup sludge.

[h] Mostly during refueling shutdown.

[i] Disposable radwaste ion-exchange unit substituting for evaporator while it is out of service.

APPENDIX B. HISTORICAL DATA TABLES FOR THE INDIVIDUAL REACTORS INCLUDING: FIRST CRITICALITY, ANNUAL AND CUMMULATIVE THERMAL OUTPUT, SOLID RADIOACTIVE WASTE GENERATION, NUMBER OF OFFSITE SHIPMENTS, AS WELL AS WASTE CORE COMPONENTS AND STRUCTURALS SHIPPED OFFSITE

Page

Table B-1. Amount of solid radioactive waste compared with gross thermal energy produced at Yankee-Rowe through December 31, 1977

Location: Rowe, Massachusetts
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 600 MW(t), 175 MW(e) net
Initial criticality: August 19, 1960

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1960	3.	3.	0.0	0.0	126852.	126852.	1.	1.
1961	17.	19.	0.1	0.1	2992983.	3119835.	3.	4.
1962	108.	127.	1.0	1.1	2321242.	5441077.	7.	11.
1963	132.	259.	5.0	6.1	3287372.	8728449.	11.	22.
1964	108.	367.	95.0	101.1	4200951.	12929400.	8.	30.
1965	147.	514.	107.0	208.1	3400357.	16329757.	12.	42.
1966	94.	608.	6.0	214.1	4514275.	20844032.	12.	54.
1967	178.	786.	6.0	220.1	4507719.	25351744.	19.	73.
1968	107.	893.	15.0	235.1	4290227.	29641968.	12.	85.
1969	123.	1016.	163.0	398.1	3959567.	33601520.	15.	100.
1970	110.	1126.	4.0	402.1	4127520.	37729040.	10.	110.
1971	127.	1253.	3.0	405.1	5016512.	42745552.	8.	118.
1972	222.	1475.	2.0	407.1	2396226.	45141776.	18.	136.
1973	176.	1651.	3.4	410.5	3571673.	48713440.	14.	150.
1974	218.	1869.	128.0	538.5	3073901.	51787328.	24.	174.
1975	263.	2132.	3.3	541.8	4020421.	55807744.	11.	185.
1976	305.	2437.	17.0	558.8	4250085.	60057824.	25.	210.
1977	285.	2722.	6.8	565.6	3516596.	63574416.	14.	224.

Table B-2. Amount of solid radioactive waste compared with gross thermal energy produced at Indian Point 1, 2, & 3 through December 31, 1977

Location: Buchanan, New York
Type: Pressurized water reactor, Unit 1 supplied by Babcock & Wilcox Company; Units 2 & 3 supplied by Westinghouse Electric Corporation

Power: Unit 1, 615 MW(t), 265 MW(e) net; Unit 2, 2758 MW(t), 873 MW(e) net; Unit 3, 3015 MW(t), 965 MW(e) net
Initial criticality: Unit 1, August 2, 1962; Unit 2, May 22, 1973; Unit 3, April 6, 1976

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1962	0.	0.	0.0	0.0	216679.	216679.	0.	0.
1963	0.	0.	0.0	0.0	2148129.	2364808.	0.	0.
1964	23.	23.	0.5	0.5	1374070.	3738878.	3.	3.
1965	42.	66.	1.0	1.5	2468285.	6207163.	5.	8.
1966	56.	122.	2.0	3.5	2613400.	8820563.	5.	13.
1967	30.	152.	0.6	4.1	3677371.	12497934.	3.	16.
1968	32.	184.	22.0	26.1	3475288.	15973222.	4.	20.
1969	27.	210.	0.8	26.9	3762765.	19735984.	2.	22.
1970	24.	235.	6.0	32.9	794519.	20530496.	2.	24.
1971	16.	251.	2.0	34.9	2867507.	23398000.	1.	25.
1972	191.[a]	442.	156.6[a]	191.5	2653864.	26051856.	7.[b]	32.
1973	412.	854.	208.1	399.6	1472902.	27524752.	12.[b]	44.
1974[c]	446.	1300.	61.9	461.5	14383222.	41907968.	27.	71.
1975	622.	1922.	2003.0	2464.5	16451574.	58359536.	76.	147.
1976	919.	2841.	945.0	3409.5	13475334.	71834864.	62.	209.
1977	1057.	3898.	1447.7	4857.2	35019376.	106854240.	93.	302.

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[a] Totals for 15 months (October 1 1971 through December 31, 1972).

[b] Number of shipments not reported for October 1, 1972 through June 30, 1973.

[c] Unit 1 shut down since October 31, 1974; fuel unloading commenced January 1, 1975.

Table B-3. Amount of solid radioactive waste compared with gross thermal energy produced at San Onofre 1 through December 31, 1977

Location: San Clemente, California
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 1347 MW(t), 430 MW(e) net
Initial criticality: June 14, 1967

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1967	0.	0.	0.0	0.0	1183703.	1183703.	0.	0.
1968	11.	11.	2.0	2.0	4046499.	5230202.	0.[a]	0.
1969	40.	51.	8.0	10.0	7898832.	13129034.	3.	3.
1970	41.	92.	11.0	21.0	9191990.	22321024.	0.[a]	3.
1971	23.	115.	2.0	23.0	9956701.	32277712.	0.[a]	3.
1972	117.	232.	80.0	103.0	8528772.	40806480.	0.[a]	3.
1973	113.	345.	381.0	484.0	7090177.	47896656.	13.	16.
1974	68.	413.	230.0	714.0	9758530.	57655184.	11.	27.
1975	80.	493.	26.0	740.0	10032025.	67687200.	6.	33.
1976	142.	635.	698.0	1438.0	7749021.	75436208.	9.	42.
1977	119.	754.	42.1	1480.1	7288243.	82724448.	14.	56.

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[a] Not reported.

Table B-4. Amount of solid radioactive waste compared with gross thermal energy produced at Connecticut Yankee (Haddam Neck) through December 31, 1977

Location: Haddam Neck, Connecticut
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 1825 MW(t), 575 MW(e) net
Initial criticality: July 24, 1967

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1967	0.	0.	0.0	0.0	1697464.	1697464.	0.	0.
1968	12.	12.	0.1	0.1	9492857.	11190321.	1.	1.
1969	83.	95.	51.0	51.1	11544534.	22734848.	7.	8.
1970	59.	154.	316.0	367.1	11406386.	34141232.	11.	19.
1971	104.	258.	274.0	641.1	13416373.	47557600.	14.	33.
1972	188.	446.	4769.0	5410.1	13780524.	61338112.	21.	54.
1973	159.	605.	571.0	5981.1	7728611.	69066720.	11.	65.
1974	204.	809.	941.6	6922.7	14157150.	83223856.	24.	89.
1975	624.	1434.	1324.4	8247.1	13402843.	96626688.	33.	122.
1976	766.	2200.	746.2	8993.3	12964154.	109590832.	40.	162.
1977	1660.	3860.	801.9	9795.2	12987491.	122578320.	83.	245.

Table B-5. Amount of solid radioactive waste compared with gross thermal energy produced at R. E. Ginna through December 31, 1977

Location: Ontario, New York
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 1300 MW(t), 420 MW(e) net
Initial criticality: November 9, 1969

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1969	0.	0.	0.0	0.0	153720.	153720.	0.	0.
1970	51.	51.	5.0	5.0	6840240.	6993960.	3.	3.
1971	702.	753.	47.0	52.0	8504065.	15498025.	24.	27.
1972	366.	1120.	1412.0	1464.0	7707240.	23205264.	51.	78.
1973	198.	1318.	599.1	2063.1	10748127.	33953376.	29.	107.
1974	275.	1593.	613.6	2676.7	6712560.	40665936.	26.	133.
1975	458.	2051.	137.6	2814.3	9706555.	50372480.	22.	155.
1976	280.	2331.	97.8	2912.1	6984360.	57356832.	23.	178.
1977	349.	2680.	689.2	3601.3	11081808.	68438640.	20.	198.

Table B-6. Amount of solid radioactive waste compared with gross thermal energy produced at H. B. Robinson 2 through December 31, 1977

Location: Harisville, South Carolina
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 2200 MW(t), 700 MW(e) net
Initial criticality: September 20, 1970

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1970	0.	0.	0.0	0.0	63694.	63694.	0.	0.
1971	24.	24.	0.0	0.0	7850675.	7914369.	2.	2.
1972	70.	94.	0.0	0.0	15536932.	23451296.	5.	7.
1973	320.	414.	96.8	96.8	12455309.	35906592.	31.	38.
1974	352.	767.	197.0	293.8	15551544.	51458128.	29.	67.
1975	356.	1122.	1337.9	1631.6	13588661.	65046784.	44.	111.
1976	316.	1439.	62.9	1694.5	15867245.	80914016.	23.	134.
1977	259.	1698.	1241.7	2936.3	14278810.	95192816.	35.	169.

Table B-7. Amount of solid radioactive waste compared with gross thermal energy produced at Point Beach 1 & 2 through December 31, 1977

Location: Two Creeks, Wisconsin
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 1518 MW(t), 497 MW(e) net, each
First criticality: Unit 1, November 2, 1970; Unit 2, May 30, 1972

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1970	0.	0.	0.0	0.0	632255.	632255.	0.	0.
1971	76.	76.	4.0	4.0	10025688.	10657943.	6.	6.
1972	193.	270.	214.0	218.0	9959016.	20616944.	15.	21.
1973	295.	565.	1829.8	2047.8	18431088.	39048032.	19.	40.
1974	132.	697.	2121.0	4168.8	20354064.	59402096.	12.	52.
1975	408.	1105.	8226.8	12395.6	20919072.	80321168.	29.	81.
1976	193.	1298.	304.1	12699.7	21805520.	102126688.	17.	98.
1977	194.	1492.	567.9	13267.6	22236336.	124363024.	14.	112.

Table B-8. Amount of solid radioactive waste compared with gross thermal energy produced at Palisades through December 31, 1977

Location: Covert, Michigan
Type: Pressurized water reactor supplied by Combustion Engineering, Inc.

Power: 2212 MW(t), 700 MW(e) net
Initial criticality: May 24, 1971

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1971	0.	0.	0.0	0.0	800.	800.	0.	0.
1972	10.	10.	2.0	2.0	5917792.	5918592.	2.	2.
1973	63.[a]	73.	37.8[a]	39.8	7799520.	13718112.	9.[a]	11.
1974	392.	465.	29.1	68.9	395448.	14113560.	24.	35.
1975	801.	1266.	222.2	291.1	8906400.	23019952.	57.	92.
1976	679.	1945.	53.2	344.3	9663024.	32682976.	43.	135.
1977	443.	2388.	87.1	431.5	17338672.	50021648.	27.	162.

[a] No data reported for January-May 1973; June data incomplete.

Table B-9. Amount of solid radioactive waste compared with gross thermal energy produced at Surry 1 & 2 through December 31, 1977

Location: Gravel Neck, Virginia
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 2441 MW(t), 788 MW(e) net, each
Initial criticality: Unit 1, July 1, 1972; Unit 2, March 7, 1973

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1972	0.	0.	0.0	0.0	1249910.	1249910.	0.	0.
1973	364.	364.	1.6	1.6	21792544.	23042448.	28.	28.
1974	1192.[a]	1556.	50.6	52.2	19164976.	42207424.	65.	93.
1975	8062.[b]	9618.	2640.0	2692.2	29010608.	71218032.	86.	179.
1976	699.	10317.	617.0	3309.2	25142160.	96360192.	101.	280.
1977	459.[c]	10776.	302.5[a]	3611.7	30418240.	126778432.	51.[a]	331.

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[a] In addition, ~14,500 gal of liquid were shipped to Morehead, Kentucky for solidification.

[b] In addition, ~40,500 gal of liquid were shipped to Morehead, Kentucky for solidification.

[c] Data not available for July-December 1977. Annual Operating Report for 1977 (Docket No. 50280-936) contains January-June 1977 data in duplicate.

Table B-10. Amount of solid radioactive waste compared with gross thermal energy produced at Turkey Point 3 & 4 through December 31, 1977

Location: Florida City, Florida
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 2200 MW(t), 693 MW(e) net, each
Initial criticality: Unit 3, October 20, 1972; Unit 4, June 11, 1973

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1972	0.	0.	0.0	0.0	353613.	353613.	0.	0.
1973	233.	233.	4.0	4.0	15463524.	15817137.	12.	12.
1974	449.	682.	44.7	48.7	25474944.	41292080.	22.	34.
1975	887.	1569.	103.7	152.4	27802272.	69094352.	50.	84.
1976	1440.	3010.	477.0	629.4	26828048.	95922400.	73.	157.
1977	0.[a]	3010.	0.0[a]	629.4	27070896.	122993296.	42.[b]	199.

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[a] No data reported for January-June 1977; reporting method precludes calculation of totals for the year because each report is directly dependent upon the one immediately preceding it and totals are obtained by difference.

[b] For July-December 1977 only.

Table B-11. Amount of solid radioactive waste compared with gross thermal energy produced at Maine Yankee through December 31, 1977

Location: Wiscasset, Maine
Type: Pressurized water reactor supplied by Combustion Engineering, Inc.

Power: 2440 MW(t), 790 MW(e) net
Initial criticality: October 23, 1972

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1972	0.	0.	0.0	0.0	1439873.	1439873.	0.	0.
1973	67.	67.	3.2	3.2	10814888.	12254761.	5.	5.
1974	159.	226.	530.4	533.6	11385475.	23640224.	14.	19.
1975	231.	457.	1478.3	2011.9	14699943.	38340160.	30.	49.
1976	180.	637.	503.8	2515.7	19452768.	57792928.	16.	65.
1977	182.	818.	87.6	2603.3	16482093.	74275008.	18.	83.

Table B-12. Amount of solid radioactive waste compared with gross thermal energy produced at Oconee 1, 2, & 3 through December 31, 1977

Location: Seneca, South Carolina
Type: Pressurized water reactor supplied by Babcock & Wilcox Company

Power: 2568 MW(t), 886 MW(e) net, each
Initial criticality: Unit 1, April 19, 1973; Unit 2, November 11, 1973; Unit 3, September 5, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1973	264.	264.	32.3	32.3	6010881.	6010881.	24.	24.
1974	571.	835.	218.3	250.6	16978176.	22989056.	97.	121.
1975	1416.	2250.	1680.6	1931.2	46825552.	69814608.	104.	225.
1976	2225.	4475.	782.7	2713.9	39705024.	109519632.	168.	393.
1977	1059.[a]	5534.	7366.7[a]	10080.6	40039856.	149559488.	160.[a]	553.

[a] No data available for January-June 1977.

Table B-13. Amount of solid radioactive waste compared with gross thermal energy produced at Zion 1 & 2 through December 31, 1977

Location: Zion, Illinois
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 3250 MW(t), 1050 MW(e) net, each
Initial criticality: Unit 1, June 19, 1973; Unit 2, December 24, 1973

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1973	417.	417.	0.2	0.2	2730096.	2730096.	33.	33.
1974	1616.	2032.	4.6	4.8	16868080.	19598176.	58.	91.
1975	1580.	3612.	15.4	20.2	32801776.	52399952.	105.	196.
1976	2454.	6066.	68.2	88.4	31059248.	83459200.	155.	351.
1977	1973.	8039.	224.8	313.2	36653232.	120112432.	193.	544.

Table B-14. Amount of solid radioactive waste compared with gross thermal energy produced at Fort Calhoun through December 31, 1977

Location: Fort Calhoun, Nebraska
Type: Pressurized water reactor supplied by Combustion Engineering, Inc.

Power: 1420 MW(t), 457 MW(e) net
Initial criticality: August 5, 1973

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1973	45.	45.	0.0[a]	0.0	2028958.	2028958.	2.	2.
1974	323.	368.	10.0	10.0	7558149.	9587107.	18.	20.
1975	537.	905.	56.1	66.1	6711976.	16299083.	35.	56.
1976	571.	1476.	97.8	163.9	7146813.	23445888.	48.	104.
1977	597.	2073.	646.0	809.9	9402613.	32848496.	51.	155.

[a] Total activity was <0.05 Ci.

Table B-15. Amount of solid radioactive waste compared with gross thermal energy produced at Prairie Island 1 & 2 through December 31, 1977

Location: Red Wing, Minnesota
Type: Pressurized water reactor supplied by Westinghouse
Electric Corporation

Power: 1650 MW(t), 530 MW(e) net, each
Initial criticality: Unit 1, December 1, 1973;
Unit 2, December 17, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1973	0.	0.	0.0	0.0	0.	0.	0.	0.
1974	135.	135.	7.6[a]	7.6	5303648.	5303648.	10.	10.
1975	150.	285.	34.7	42.3	22547328.	27850976.	13.	23.
1976	152.	437.	50.3	92.6	20580896.	48431872.	13.	36.
1977	643.	1080.	245.9	338.5	24646080.	73077952.	25.	61.

Table B-16. Amount of solid radioactive waste compared with gross thermal energy produced at Kewaunee through December 31, 1977

Location: Carlton, Wisconsin
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 1650 MW(t), 541 MW(e) net
Initial criticality: March 7, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1974	0.[a]	0.	0.0[a]	0.0	6159068.	6169068.	0.[a]	0.
1975	16.	16.	2.1	2.1	10820769.	16989824.	1.	1.
1976	503.	519.	39.2	41.3	10806217.	27796032.	5.	6.
1977	34.	553.	366.3	407.6	11133942.	38929968.	4.	10.

[a] No data for July-December 1974.

Table B-17. Amount of solid radioactive waste compared with gross thermal energy produced at Three Mile Island 1 through December 31, 1977

Location: Middletown, Pennsylvania
Type: Pressurized water reactor supplied by Babcock & Wilcox Company

Power: 2535 MW(t), 819 MW(e) net
Initial criticality: June 5, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1974	200.	200.	6.1	6.1	7920380.	7920360.	16.	16.
1975	458.	658.	257.8	263.9	17635184.	25555552.	39.	55.
1976	406.	1064.	185.0	448.9	13926275.	39481824.	29.	84.
1977	137.[a]	1201.	34.4[a]	483.3	17635680.	57117504.	10.[a]	94.

[a] No data for July-December 1977.

Table B-18. Amount of solid radioactive waste compared with gross thermal energy produced at Arkansas Nuclear One 1 through December 31, 1977

Location: Russellville, Arkansas
Type: Pressurized water reactor supplied by Babcock & Wilcox Company

Power: 2568 MW(t), 850 MW(e) net
Initial criticality: August 6, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1974	0.	0.	0.0	0.0	1952144.	1952144.	0.	0.
1975	0.	0.	0.0	0.0	15412817.	17364960.	0.	0.
1976	123.[a]	123.	0.0[b]	0.0	12073746.	29438704.	8.	8.
1977	0.[c]	123.	0.0[c]	0.0	16439238.	45877936.	0.[c]	8.

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[a] Stored spent resins onsite and shipped liquids as necessary until fall of 1976; dry waste not reported.

[b] Curie content not reported.

[c] No data available for entire year 1977.

Table B-19. Amount of solid radioactive waste compared with gross thermal energy produced at Rancho Seco through December 31, 1977

Location: Clay Station, California
Type: Pressurized water reactor supplied by Babcock & Wilcox Company

Power: 2452 MW(t), 804 MW(e) net
Initial criticality: September 16, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1974	0.[a]	0.	0.0	0.0	946262.	946262.	0.	0.
1975	0.[b]	0.	0.1	0.1	8012553.	8958815.	1.	1.
1976	110.[c]	110.	20.4	20.6	6908230.	15867045.	6.	7.
1977	40.[d]	150.	1151.1	1171.7	18117168.	33984208.	2.	9.

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[a] No solid waste shipped, but 10,245 gal of liquid containing 0.15 Ci (mostly tritium) were shipped in 4 shipments to Beatty, Nevada for solidification.

[b] Resin volume was <0.5 m^3; in addition ~97,800 gal of liquid containing ~16.6 Ci were shipped in 33 shipments to Beatty, Nevada for solidification.

[c] ~96,000 gal of liquid containing ~16.4 Ci were also shipped in 32 shipments to Beatty, Nevada for solidification.

[d] ~110,000 gal of liquid containing ~69.0 Ci were shipped in 37 shipments to Beatty, Nevada for solidification.

Table B-20. Amount of solid radioactive waste compared with gross thermal energy produced at Calvert Cliffs 1 & 2 through December 31, 1977

Location: Lusby, Maryland
Type: Pressurized water reactor supplied by Combustion Engineering, Inc.

Power: 2570 MW(t), 845 MW(e) net, each
Initial criticality: Unit 1, October 7, 1974; Unit 2, November 30, 1976

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE: VOLUME (CUBIC METERS) ANNUAL AMOUNT	CUMULATIVE TOTAL	RADIOACTIVITY (CURIES) ANNUAL AMOUNT	CUMULATIVE TOTAL	GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS) ANNUAL AMOUNT	CUMULATIVE TOTAL	NUMBER OF SHIPMENTS ANNUAL NUMBER	CUMULATIVE TOTAL
1974	0.	0.	0.0	0.0	38.	38.	0.	0.
1975	0.[a]	0.	0.0[a]	0.0	14021092.	14021130.	0.[a]	0.
1976	118.	118.	122.0	122.0	20191824.	34212944.	8.	8.
1977	180.[b]	298.	1.9[b]	123.9	29737984.	63950928.	11.[b]	19.

[a] Not available for July-December, 1975.

[b] Not available for July-December 1977.

Table B-21. Amount of solid radioactive waste compared with gross thermal energy produced at Donald C. Cook 1 through December 31, 1977

Location: Benton Harbor, Michigan
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 3250 MW(t), 1060 MW(e) net
Initial criticality: January 18, 1975

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE: VOLUME (CUBIC METERS) ANNUAL AMOUNT	CUMULATIVE TOTAL	RADIOACTIVITY (CURIES) ANNUAL AMOUNT	CUMULATIVE TOTAL	GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS) ANNUAL AMOUNT	CUMULATIVE TOTAL	NUMBER OF SHIPMENTS ANNUAL NUMBER	CUMULATIVE TOTAL
1975	172.	172.	0.6	0.6	14593832.	14593832.	9.	9.
1976	193.	365.	25.8	26.4	21484032.	36077856.	16.	25.
1977	684.	1049.	82.8	109.2	15478323.	51556176.	47.	72.

Table B-22. Amount of solid radioactive waste compared with gross thermal energy produced at Millstone Point 2 through December 31, 1977

Location: Waterford, Connecticut
Type: Pressurized water reactor supplied by Combustion Engineering, Inc.

Power: 2560 MW(t), 828 MW(e) net
Initial criticality: October 17, 1975

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1975	0.	0.	0.0	0.0	639533.	639533.	0.	0.
1976	758.[a]	758.	7.6[a]	7.6	15155524.	15795057.	26.	26.
1977	94.[b]	852.	58.0[b]	65.6	14235801.	30030848.	12.[b]	38.

[a] Includes dry compressible wastes shipped via Unit 1.

[b] Dry compressible wastes not included.

Table B-23. Amount of solid radioactive waste compared with gross thermal energy produced at Trojan through December 31, 1977

Location: Prescott, Oregon
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 3423 MW(t), 1130 MW(e) net
Initial criticality: December 15, 1975

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1975	0.	0.	0.0	0.0	0.	0.	0.	0.
1976	44.	44.	4.3	4.3	7540494.	7540494.	6.	6.
1977	101.	145.	83.1	87.4	21237280.	28777760.	14.	20.

Table B-24. Amount of solid radioactive waste compared with gross thermal energy produced at St. Lucie 1 through December 31, 1977

Location: Hutchison Island, Florida
Type: Pressurized water reactor supplied by Combustion Engineering, Inc.

Power: 2560 MW(t), 801 MW(e) net
Initial criticality: April 22, 1976

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1976	86.	86.	1.6	1.6	347603.	347603.	5.	5.
1977	344.	430.	407.8	409.4	17501600.	17849200.	24.	29.

Table B-25. Amount of solid radioactive waste compared with gross thermal energy produced at Beaver Valley 1 through December 31, 1977

Location: Shippingport, Pennsylvania
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 2660 MW(t), 852 MW(e) net
Initial criticality: May 10, 1976

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1976	43.	43.	0.0[a]	0.0	1973248.	1973248.	2.	2.
1977	267.	310.	8.2	8.2	10106245.	12079493.	16.	18.

[a] Annual total <0.05 Ci.

Table B-26. Amount of solid radioactive waste compared with gross thermal energy produced at Salem 1 through December 31, 1977

Location: Salem, New Jersey
Type: Pressurized water reactor supplied by Westinghouse Electric Corporation

Power: 3350 MW(t), 1090 MW(e) net
Initial criticality: December 11, 1976

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1976	0.	0.	0.0	0.0	48697.	48697.	0.	0.
1977	0.[a]	0.	0.0[a]	0.0	6695220.	6743917.	0.[a]	0.

[a] No data available for July-December 1977.

Table B-27. Amount of solid radioactive waste compared with gross thermal energy produced at Crystal River 3 through December 31, 1977

Location: Crystal River, Florida
Type: Pressurized water reactor supplied by Babcock & Wilcox Company

Power: 2452 MW(t), 852 MW(e) net
Initial criticality: January 14, 1977

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1977	448.	448.	3.5	3.5	12628091.	12628091.	30.	30.

Table B-28. Amount of solid radioactive waste compared with gross thermal energy produced at Davis-Besse 1 through December 31, 1977

Location: Oak Harbor, Ohio
Type: Pressurized water reactor supplied by Babcock & Wilcox Company

Power: 2789 MW(t), 906 MW(e) net
Initial criticality: November 20, 1977

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1977	0.	0.	0.0	0.0	1664032.	1664032.	0.	0.

Table B-29. Amount of solid radioactive waste compared with gross thermal energy produced at Dresden 1, 2, & 3 through December 31, 1977

Location: Murris, Illinois
Type: Boiling water reactor supported by
General Electric Company

Power: Unit 1, 700 MW(t), 200 MW(e) net; Units 2 & 3, 2527 MW(t), 809 MW(e) net, each
Initial criticality: Unit 1, October 15, 1959; Unit 2, January 7, 1970; Unit 3, January 31, 1971

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1959	0.	0.	0.0	0.0	0.	0.	0.	0.
1960	32.	32.	0.1	0.1	908887.	908887.	1.	1.
1961	94.	126.	1.1	1.2	1808575.	2717462.	7.	8.
1962	95.	222.	1.6	2.8	4032427.	6749889.	5.	13.
1963	169.	391.	1.1	3.9	3136675.	9886564.	2.	15.
1964	54.	445.	0.4	4.3	3328510.	13215074.	2.	17.
1965	94.	539.	0.6	4.9	3315583.	16530657.	4.	21.
1966	57.	596.	0.6	5.5	4781128.	21311776.	2.	23.
1967	349.	945.	13.3	18.9	2768700.	24080464.	11.	34.
1968	221.	1166.	209.0	227.9	3199385.	27279840.	12.	46.
1969	97.	1263.	282.0	509.9	2891837.	30171664.	3.	49.
1970	645.	1908.	11.6	521.4	8883730.	39055392.	28.	77.
1971	991.	2899.	51.0	572.4	14702659.	53758048.	56.	133.
1972	1605.	4504.	123.0	695.4	28955840.	82713888.	113.	246.
1973	2202.[a]	6706.	149.9	845.3	30674784.	113388672.	208.	454.
1974	2982.[b]	9688.	5055.0	5900.3	23157104.	136545776.	627.	1081.
1975	5850.	15538.	7335.4	13235.7	19472272.	156018048.	823.	1904.
1976	7086.	22624.	4332.6	17568.3	30939232.	186957280.	989.	2893.
1977	1856.	24480.	11316.8	28885.1	31034224.	217991504.	307.	3200.

[a] Volume does not include 12 resin shipments.

[b] Based on estimate of wet waste (mostly resin) volume for January-June 1974 and may be somewhat high.

Table B-30. Amount of solid radioactive waste compared with gross thermal energy produced at Big Rock Point through December 31, 1977

Location: Charlevoix, Michigan
Type: Boiling water reactor supplied by General Electric Company

Power: 240 MW(t), 70 MW(e) net
Initial criticality: September 27, 1962

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1962	0.	0.	0.0	0.0	2000.	2000.	0.	0.
1963	0.	0.	0.0	0.0	400287.	402287.	0.	0.
1964	0.	0.	0.0	0.0	629516.	1031803.	0.	0.
1965	45.	45.	379.0	379.0	593192.	1624995.	6.	6.
1966	9.	54.	2.0	381.0	1142246.	2767241.	3.	9.
1967	5.	59.	50.0	431.0	1718576.	4485817.	4.	13.
1968	65.	123.	1746.0	2177.0	1414506.	5900323.	12.	25.
1969	24.	147.	61.0	2238.0	1302207.	7202530.	3.	28.
1970	0.	148.	113.0	2351.0	1176288.	8378818.	10.	38.
1971	24.	172.	0.3	2351.3	1205599.	9584417.	1.	39.
1972	61.	232.	1128.0	3479.3	1195550.	10779967.	12.	51.
1973	5.	237.	55.9	3535.2	1414505.	12194472.	2.	53.
1974	39.	276.	94.5	3629.7	1125110.	13319582.	4.	57.
1975	70.[a]	346.	1016.8	4646.6	977036.	14296618.	16.	[illegible]
1976	29.	375.	3.7	4650.2	830079.	15126697.	3.	76.
1977	72.	447.	967.6	5617.9	1228283.	16354980.	14.	90.

[a] Estimated.

Table B-31. Amount of solid radioactive waste compared with gross thermal energy produced at Humboldt Bay through December 31, 1977

Location: Eureka, California
Type: Boiling water reactor supplied by General Electric Company

Power: 240 MW(t), 68 MW(e) net
Initial criticality: February 16, 1963

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1963	0.	0.	0.0	0.0	565344.	565344.	0.	0.
1964	18.	18.	1.0	1.0	1222440.	1787784.	1.	1.
1965	50.	69.	1.0	2.0	891922.	2679706.	1.	2.
1966	0.	69.	0.0	2.0	585086.	3264792.	0.	2.
1967	38.	107.	1.0	3.0	1126634.	4391426.	1.	3.
1968	0.	107.	2.0	5.0	1507600.	5899026.	2.	5.
1969	0.	107.	0.0	5.0	1278499.	7177525.	0.	5.
1970	40.	147.	5.0	10.0	1398874.	8576399.	2.	7.
1971	67.	214.	4.0	14.0	1140734.	9717133.	2.	9.
1972	57.	271.	5.0	19.0	1250385.	10967518.	3.	12.
1973	81.	352.	11.4	30.4	1467720.	12435238.	7.	19.
1974	51.	403.	32.4	62.7	1272490.	13707728.	5.	24.
1975	127.	530.	43.1	105.8	1321534.	15029262.	7.	31.
1976	85.	615.	4.1	109.9	681902.[a]	15711164.	3.	34.
1977	377.	992.	38.6	148.5	0.[a]	15711164.	16.	50.

[a] Shut down since July 2, 1976 for seismic modifications.

Table B-32. Amount of solid radioactive waste compared with gross thermal energy produced at La Crosse through December 31, 1977

Location: Genoa, Wisconsin
Type: Boiling water reactor supplied by Allis Chalmers Manufacturing Company

Power: 165 MW(t), 53 MW(e) net
Initial criticality: July 11, 1967

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1967	0.	0.	0.0	0.0	420.	420.	0.	0.
1968	16.	16.	0.2	0.2	21852.	22272.	2.	2.
1969	18.	34.	1.0	1.2	245784.	268056.	2.	4.
1970	19.	53.	3.0	4.2	447816.	715872.	1.	5.
1971	0.	53.	0.0	4.2	707256.	1423128.	0.	5.
1972	25.	78.	0.0	4.2	816552.	2239680.	2.	7.
1973	254.[a]	332.	42.5[a]	46.7	684528.	2924208.	11.[a]	18.
1974	42.	374.	470.9	517.6	1084349.	4008557.	5.	23.
1975	36.[b]	410.	283.0[b]	800.6	921403.	4929960.	3.[b]	26.
1976	35.[c]	445.	40.5[c]	841.1	609336.	5539296.	3.[c]	29.
1977	3.[d]	448.	573.9	1415.0	343802.	5883058.	1.	30.

[a] Estimated on the basis of incomplete data given.

[b] May be incomplete since no data was available for November 1975.

[c] No data available for 1976. This estimate is based on response to ORNL questionnaire.

[d] Estimated volume of 8360 lb spent ion-exchange resin; no dry compressible waste reported.

Table B-33. Amount of solid radioactive waste compared with gross thermal energy produced at Oyster Creek through December 31, 1977

Location: Toms River, New Jersey
Type: Boiling water reactor supplied by General Electric Company

Power: 1930 MW(t), 640 MW(e) net
Initial criticality: May 3, 1969

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1969	0.	0.	0.0	0.0	1195344.	1195344.	0.	0.
1970	218.	218.	3.0	3.0	10603148.	11798492.	0.	0.
1971	308.	526.	5.0	8.0	11679781.	23478272.	18.	18.
1972	436.	962.	1301.0	1309.0	12981053.	36459312.	45.	63.
1973	833.	1795.	2887.6	4196.6	10864995.	47324304.	153.	216.
1974	1211.	3005.	1568.9	5765.5	11124068.	58448368.	168.	384.
1975	990.	3995.	2811.9	8577.4	9807283.	68255648.	165.	549.
1976	1200.	5195.	1280.8	9858.2	11797821.	80053456.	146.	695.
1977	1743.	6938.	272.9	10131.1	9815564.	89869008.	122.	817.

Table B-34. Amount of solid radioactive waste compared with gross thermal energy produced at Nine Mile Point 1 through December 31, 1977

Location: Lycoming, New York
Type: Boiling water reactor supplied by General Electric Company

Power: 1850 MW(t), 625 MW(e) net
Initial criticality: September 5, 1969

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1969	0.	0.	0.0	0.0	294998.	294998.	0.	0.
1970	87.	87.	4.0	4.0	5940025.	6235023.	3.	3.
1971	366.	453.	201.0	205.0	9956701.	16191724.	44.	47.
1972	428.	880.	265.0	470.0	10010626.	26202336.	60.	107.
1973	545.	1425.	1010.0	1480.0	10972154.	37174480.	66.	173.
1974	452.	1877.	1933.0	3413.0	10513759.	47688224.	75.	248.
1975	446.	2323.	3250.7	6663.7	9680130.	57368352.	95.	343.
1976	538.	2861.	2509.5	9173.3	13086781.	70455120.	86.	429.
1977	659.	3519.	1586.8	10760.0	9152502.	79607616.	71.	500.

Table B-35. Amount of solid radioactive waste compared with gross thermal energy produced at Millstone Point 1 through December 31, 1977

Location: Waterford, Connecticut
Type: Boiling water reactor supplied by General Electric Company
Power: 2011 MW(t), 652 MW(e) net
Initial criticality: October 26, 1970

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1970	0.	0.	0.0	0.0	287709.	287709.	0.	0.
1971	208.	208.	95.0	95.0	11112012.	11399721.	28.	28.
1972	261.	469.	433.0	528.0	9687612.	21087328.	32.	60.
1973	445.	914.	2854.3	3382.3	5956975.	27044288.	87.	147.
1974	834.	1748.	256.8	3639.1	11160086.	38204368.	206.	353.
1975	1780.	3528.	2583.8	6222.9	12054041.	50258400.	344.	697.
1976	852.	4380.	1694.2	7917.1	11636094.	61894480.	153.	850.
1977	857.[a]	5237.	1273.2[a]	9190.3	14815973.	76710448.	137.[a]	987.

[a] No data available for July-December 1977. These values include the dry compressible wastes from Unit 2.

Table B-36. Amount of solid radioactive waste compared with gross thermal energy produced at Monticello through December 31, 1977

Location: Monticello, Minnesota
Type: Boiling water reactor supplied by General Electric Company

Power: 1670 MW(t), 545 MW(e) net
Initial criticality: December 11, 1970

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1970	0.	0.	0.0	0.0	0.	0.	0.	0.
1971	309.	309.	18.0	18.0	14871105.	14871105.	15.	15.
1972	178.	487.	88.0	106.0	10934823.	25805920.	13.	28.
1973	211.	698.	393.1	499.1	9899181.	35705088.	35.	63.
1974	268.	965.	2476.8	2975.9	8938483.	44643568.	47.	110.
1975	381.	1346.	5429.2	8405.1	8884260.	53527824.	49.	159.
1976	285.	1631.	3788.2	12193.3	12343438.	65871248.	43.	202.
1977	569.	2200.	1033.9	13227.2	10991800.	76863136.	57.	259.

Table B-37. Amount of solid radioactive waste compared with gross thermal energy produced at Quad-Cities 1 & 2 through December 31, 1977

Location: Cordova, Illinois
Type: Boiling water reactor supplied by General Electric Company

Power: 2511 MW(t), 800 MW(e) net
Initial criticality: Unit 1, October 18, 1971; Unit 2, April 26, 1972

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1971	60.	60.	0.0	0.0	988.	988.	4.	4.
1972	1075.	1134.	9.0	9.0	12521525.	12522513.	72.	76.
1973	1008.	2142.	293.3	302.4	31704528.	44227040.	158.	234.
1974	844.	2986.	737.2	1039.6	26057856.	70284896.	284.	518.
1975	1383.	4370.	2373.6	3413.2	23134880.	93419776.	465.	983.
1976	1004.	5374.	2350.9	5764.1	25858592.	119278368.	284.	1267.
1977	1375.	6749.	8221.5	13985.6	26813056.	146091424.	404.	1671.

Table B-38. Amount of solid radioactive waste compared with gross thermal energy produced at Vermont Yankee through December 31, 1977

Location: Vernon, Vermont
Type: Boiling water reactor supplied by General Electric Company

Power: 1593 MW(t), 514 MW(e) net
Initial criticality: March 24, 1972

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1972	126.	126.	18.0	18.0	1479512.	1479512.	13.	13.
1973	187.	313.	23.5	41.5	6080140.	7559652.	37.	50.
1974	198.	511.	108.4	149.9	8203177.	15762829.	35.	85.
1975	309.	820.	22.5	172.4	11267394.	27030208.	43.	128.
1976	238.	1057.	29.3	201.7	10192187.	37222384.	30.	158.
1977	253.	1310.	249.3	451.0	11118733.	48341104.	42.	200.

Table B-39. Amount of solid radioactive waste compared with gross thermal energy produced at Pilgrim 1 through December 31, 1977

Location: Plymouth, Massachusetts
Type: Boiling water reactor supplied by General Electric Company

Power: 1998 MW(t), 664 MW(e) net
Initial criticality: June 16, 1972

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED (MEGAWATT-HOURS)		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)					
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1972	68.	68.	20.0	20.0	2654184.	2654184.	4.	4.
1973	217.	285.	566.0	586.0	12539304.	15193488.	19.	23.
1974	406.	691.	1475.0	2061.0	5995608.	21189088.	34.	57.
1975	452.	1143.	3794.9	5855.9	8101800.	29290880.	67.	124.
1976	900.[a]	2043.	5429.1[a]	11285.0	7603200.	36894080.	155.[a]	279.
1977	583.	2626.	3728.3	15013.3	8258136.	45152208.	82.	361.

[a] May be incomplete since no quarterly report January-March 1976 was available.

Table B-40. Amount of solid radioactive waste compared with gross thermal energy produced at Browns Ferry 1, 2, & 3 through December 31, 1977

Location: Decatur, Alabama
Type: Boiling water reactor supplied by General Electric Company

Power: 3293 MW(t), 1065 MW(e) net, each
Initial criticality: Unit 1, August 17, 1973; Unit 2, July 20, 1974; Unit 3, August 8, 1976

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1973	78.	78.	8.3	8.3	1374432.	1374432.	18.	18.
1974	461.	539.	84.1	92.4	20166960.	21541392.	113.	131.
1975[a]	1273.	1812.	1348.3	1440.7	8754696.	30296080.	121.	252.
1976[a]	2427.[b]	4239.	102.8	1543.5	13441385.	43737456.	142.	394.
1977	1715.[c]	5954.	1675.5	3219.0	53767680.	97505136.	153.	547.

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[a] Units 1 & 2 were down for repairs from March 22, 1975 to September 14, 1976 and August 25, 1976, respectively.

[b] Assumed that 1766 boxes each had a volume of 23.5 ft^3 (i.e., same size as the boxes shipped in 1975).

[c] Assumed that 1366 boxes each had a volume of 23.5 ft^3 (i.e., same size as the boxes shipped in 1975).

Table B-41. Amount of solid radioactive waste compared with gross thermal energy produced at Peach Bottom 2 & 3 through December 31, 1977

Location: Peach Bottom, Pennsylvania
Type: Boiling water reactor supplied by General Electric Company

Power: 3294 MW(t), 1065 MW(e) net, each
Initial criticality: Unit 1, September 16, 1973; Unit 2, August 8, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1973	30.	30.	0.3	0.3	250.	250.	4.	4.
1974	397.	427.	58.0	58.3	19859872.	19860112.	41.	45.
1975	582.	1009.	217.0	275.3	33409632.	53269744.	68.	113.
1976	1198.	2207.	1159.9	1435.2	37198368.	90468112.	203.	316.
1977	2524.	4731.	1824.0	3259.2	28590496.	119058608.	301.	617.

Table B-42. Amount of solid radioactive waste compared with gross thermal energy produced at Cooper through December 31, 1977

Location: Brownville, Nebraska
Type: Boiling water reactor supplied by General Electric Company

Power: 2381 MW(t), 778 MW(e) net
Initial criticality: February 21, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1974	379.	379.	17.2	17.2	6903277.	6903277.	26.	26.
1975	290.	669.	266.3	283.5	12445810.	19349072.	36.	62.
1976	301.	970.	320.5	604.0	11850347.	31199408.	38.	100.
1977	284.	1254.	285.1	889.1	14476104.	45675504.	43.	143.

Table B-43. Amount of solid radioactive waste compared with gross thermal energy produced at Duane Arnold through December 31, 1977

Location: Palo, Iowa
Type: Boiling water reactor supplied by General Electric Company

Power: 1593 MW(t), 535 MW(e) net
Initial criticality: March 23, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1974	321.	321.	61.4	61.4	4542720.	4542720.	26.	26.
1975	261.	582.	81.0	142.4	7420728.	11963448.	22.	48.
1976	595.	1177.	187.3	329.7	8023776.	19987216.	43.	91.
1977	545.	1722.	498.2	827.9	9324816.	29312032.	51.	142.

Table B-44. Amount of solid radioactive waste compared with gross thermal energy produced at Edwin Hatch 1 through December 31, 1977

Location: Baxley, Georgia
Type: Boiling water reactor supplied by General Electric Company

Power: 2436 MW(t), 786 MW(e) net
Initial criticality: September 12, 1974

	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
YEAR	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1974	128.	128.	8.3	8.3	233159.	233159.	7.	7.
1975	583.	711.	271.3	279.6	9780130.	10013289.	31.	38.
1976	411.	1122.	289.1	568.7	13770699.	23783984.	28.	66.
1977	538.	1660.	371.7	940.5	12174595.	35958576.	39.	105.

Table B-45. Amount of solid radioactive waste compared with gross thermal energy produced at FitzPatrick through December 31, 1977

Location: Lycoming, New York
Type: Boiling water reactor supplied to General Electric Company

Power: 2436 MW(t), 821 MW(e) net
Initial criticality: November 17, 1974

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1975	510.	510.	132.0	132.0	6807986.	6807986.	44.	44.
1976	619.	1129.	341.2	473.2	12637857.	19445840.	127.	171.
1977	1217.	2346.	1453.2	1926.4	11782792.	31228624.	102.	273.

Table B-46. Amount of solid radioactive waste compared with gross thermal energy produced at Brunswick 1 & 2 through December 31, 1977

Location: Southport, North Carolina
Type: Boiling water reactor supplied by General Electric Company

Power: 2436 MW(t), 821 MW(e) net, each
Initial criticality: Unit 1, October 8, 1976; Unit 2, March 20, 1975

YEAR	GROSS SOLID WASTE SHIPPED OFFSITE				GROSS THERMAL ENERGY PRODUCED		NUMBER OF SHIPMENTS	
	VOLUME (CUBIC METERS)		RADIOACTIVITY (CURIES)		(MEGAWATT-HOURS)			
	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL AMOUNT	CUMULATIVE TOTAL	ANNUAL NUMBER	CUMULATIVE TOTAL
1975	391.	391.	47.8	47.8	4718698.	4718698.	35.	35.
1976	1784.	2175.	640.2	687.9	7968336.	12687034.	109.	144.
1977	2449.	4624.	2615.0	3302.9	15853911.	28540944.	223.	367.

Table B-47. Waste core components and structurals[a] from PWRs and BWRs reported as shipped offsite for burial as of December 31, 1977

Installation	Core component shipments			
	Total volume (m^3)	Total activity (Ci)	Total (number)	Dates [year(s)]
PWRs:				
Yankee-Rowe	$\gg$64 (plus 11 casks)	258,497	>11	1963, 1964, 1966, 1967, 1968, 1973, 1976
San Onofre	*b*	6	1	1968
Connecticut Yankee	18.5	39	*b*	1977
Palisades	0.9	4,989	*b*	1974, 1976
Maine Yankee	5.8	20,100	*b*	1976, 1977
Kewaunee	90.2	10.4	*b*	1976
Rancho Seco	1.7	7.3	*b*	1976
Calvert Cliffs	14.2	63.6	*b*	1977[c]
St. Lucie	~6	2,862	11	1977
Total	>201.3	295,535.3		1960–1977
BWRs:				
Dresden	>74	28,676	25	1961, 1962, 1965, 1977[d]
Big Rock Point	>5 (plus 2 casks)	52,046	53	1965, 1966, 1970, 1972, 1973[d]
Humboldt Bay	0.2	983	2	1964, 1968
LaCrosse	*e*	14,606	2	1977
Oyster Creek	7.1	137,000	17	1977
Nine Mile Point	6.2	18,710	*b*	1977
Millstone 1	422	0.1	*b*	1974
Monticello	4.4	28,100	7	1977
Vermont Yankee	3.4	80,100	*b*	1977
Pilgrim	12.8	33,437	*b*	1976, 1977
Browns Ferry	11.3	9,918	*b*	1977
Cooper	9.4	3,469	*b*	1977
Hatch	1.1	11.2	*b*	1975, 1976, 1977
FitzPatrick	12.7	4,720	~9	1977
Brunswick	11.7	620	*b*	1975, 1976, 1977
Total	>581.3	412,396.3		1959–1977

[a] Includes curtains, shrouds, control rods, control rod blades, control rod channels, fuel channels, in-core chambers, flux wires, source pins, support tubes, thermal shield and hold-down device, control rod drive index tubes, in-core wire, dummy fuel rods, orifices, stiffeners, channel plugs, channel pieces, transition pieces, etc.

[b] Not reported.

[c] January–June only.

[d] Volume not reported for 1973.

[e] 4299 kg; volume not reported.

APPENDIX C. LIST OF ORGANIZATIONS CONTRIBUTING TO THE SURVEY

The following organizations and members of their staffs made helpful contributions to the material contained in this survey:

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Florida Power & Light Co.
Georgia Power Co.
Gulf States Utilities Co.
Houston Lighting & Power Co.
Illinois Power Co.
Indiana and Michigan Electric Co.
Iowa Electric Light & Power Co.
Jersey Central Power & Light Co. (GPU Services Corp.)
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Power Authority of State of New York
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Southern California Edison Co.
Tennessee Valley Authority
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- Union Electric Co.
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- Wisconsin Public Service Corp.
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