NUREG/CR-0141
ORNL/NUREG-41

The Use of Filtration to Treat Radioactive Liquids in Light-Water-Cooled Nuclear Reactor Power Plants

A. H. Kibbey
H. W. Godbee

Prepared for
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Safeguards, Fuel Cycle and Environmental Research
Under Interagency Agreement DOE 40-550-75

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161

NUREG/CR-0141
ORNL/NUREG-41
Dist. Category RR

Contract No. W-7405-eng-26

Chemical Technology Division

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Manuscript Submitted: May 1978

Date Published: September 1978

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NRC FIN No. B0171

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THE USE OF FILTRATION TO TREAT RADIOACTIVE LIQUIDS IN LIGHT-WATER-COOLED NUCLEAR REACTOR POWER PLANTS

A. H. Kibbey
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ABSTRACT

A survey was made to investigate the current and future use of filtration as a method for treating liquid radioactive streams at light-water-cooled nuclear reactor (LWR) power plants. Pertinent data were obtained by contacting utility companies, nuclear-steam-supply system vendors, architect-engineers, as well as filter manufacturers and vendors. Principal interest was placed upon obtaining operating data on the performance of filters used to treat radioactive liquid streams at LWR plants containing from essentially none up to 2000 ppm suspended solids.

Included in this report are characteristics of the streams filtered at both pressurized water reactor (PWR) and boiling water reactor (BWR) plants and the filter requirements for these streams. The many types of filters used, or proposed, for treating radioactive liquids at LWRs are described. To facilitate the collation and interpretation of data, filters are categorized as disposable or reusable in this report. Filters with disposable cartridge elements made of fiber or paper have been the most widely used, especially in PWR plants. Reusable filters with and without precoat (an initial porous cake on the filter element) have also been widely used, especially at BWR plants.

Operating data presented include criteria for changeout, backflush, or replacement of the filter medium; frequency and time requirement for these operations; personnel exposures and doses during these operations; as well as the volumes of wastes (solid, liquid, and gaseous) generated. The survey shows that filtration cycles are terminated on the basis of the radioactivity level in the vicinity of the filter, the pressure drop across the filter, or convenience in plant operation, and not on the basis of filter performance in reducing radioactivity in the stream (e.g., as expressed by a decontamination factor).

Limited data were obtained on the properties (e.g., size, size distribution, shape, and concentration of suspended solids) of the streams being filtered at LWRs although these properties are among the most important in selection of a filter medium. Many different methods using a wide variety of test solids are used to evaluate the efficiency, or stopping power, of a filter medium, and there is no consensus as to which is the most reliable and meaningful for rating a given medium.

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1. SUMMARY AND RECOMMENDATIONS

Operating and design data on filters were collected by direct contacts with 65 organizations including suppliers of nuclear-steam-supply systems, architect-engineers, filter manufacturers and vendors, as well as operators of present and proposed light-water-cooled nuclear reactor (LWR) power plants. The main reason for this survey was to obtain operating data so that evaluations can be made of the effectiveness of liquid filtration in reducing the releases of radioactivity to the environment from nuclear power plants.

Characterization of the various liquid streams normally treated by filtration in terms of the concentration of suspended solids ("contaminant," "crud," or "dirt") and the particle-size distribution of these solids is rather limited although 46 plants representing 65 reactors were in operation (December 31, 1977). Even more limited is information on the solids load of filters [weight (or curies) of filterable solids per unit surface (or volume) of filter medium]. A very limited amount of information on decontamination factor (DF), the ratio of radioactive filterable solids in the influent to radioactive filterable solids in the effluent, is available. The report includes a general description of filters used, or proposed for use, in LWR plants. Criteria for filter element changeout or replacement, the frequency and time requirement for these operations, radioactive exposures and doses during these operations, as well as characterization of the radwaste generated by them, are included. The basic theoretical and design factors influencing filter selection and performance are presented.

The results of this survey on the use of filtration to treat radioactive liquids in LWR nuclear power plants show that the nearly exclusive use of disposable cartridge-type filters combined with deep-bed ion-exchange units in process stream purification at pressurized water reactor (PWR) plants has undergone some changes in recent years. Poor filter arrangement within some plants and less than satisfactory equipment for performing filter media changeouts were frequently the cause of increases in personnel exposures. The contact dose rates of these

filters have been as high as a hundred R/hr, and the changeout operation was largely a manual maneuver. Some PWRs have moved toward combination filter/powdered-resin units which are amenable to automatic remote operation; others have chosen backflushable stacked etched-disc filters to replace some of the cartridges, and still others have revamped their original plant equipment to achieve better performance. At boiling water reactor (BWR) plants, filter plugging, loss of filter cake due to fluctuations in pressure or flow, migration of precoat fines, and deformation of the filter elements because of uneven loading are among the difficulties that have been encountered in filtration operations. The BWRs, too, have experienced changes similar to those that have taken place at PWRs: adoption of the filter/powdered-resin units, installation of stacked etched-disc backflushable filters, and replacement or rearrangement of original plant equipment. More BWRs use powdered-resin ion exchangers for stream cleanup than do PWRs; cartridge filters are still the dominant means of stream cleanup at PWRs.

In addition to the general trends described above, based on the information gathered in the survey, the following observations can be made:

(1) Filter types that cannot be easily adapted to remote operation within shielded areas or that require frequent maintenance by manual contact are not well suited to nuclear service. Most commercially available filters, however, do perform satisfactorily when the nuclear constraints (shielding and remote operation) are met.

(2) Filter/demineralizers, which combine filtration and ion exchange into a single unit operation using nonregenerable powdered resins, have grown in popularity and are now being used in applications at LWR plants where, formerly, pressure-precoat or disposable cartridge filters followed by deep-bed bead-resin ion-exchange units were routinely used. Discussion of filter/demineralizers is beyond the scope of this report, and they are mentioned herein only when necessary to the interpretation of conventional-type (mechanical separation of liquid and solid) filter data.

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(3) Suspended solids concentrations in the LWR streams considered in this survey varied from a few ppb in reactor primary systems to the 1500-2000 ppm found occasionally in floor drain wastes where the average usually ranges from 70-200 ppm.

(4) Particle size and size-distribution data on the solids filtered at LWR plants are limited. The data on suspended solids in PWR primary coolant give mean particle sizes of about 1, 4, and 5 μm on a count basis which correspond to 5, 17, and 22 μm, respectively, on a weight basis.

(5) Flow rates of the streams which are filtered at LWRs may be as low as 2-3 gpm for the coolant-pump-seal injection and return lines or as high as tens of thousands of gpm in the condensate polishing systems where multiple treatment units are used. The rates for most of the other filtered streams, however, usually fall in the range of 30-400 gpm.

(6) Temperatures of the filtered streams usually are less than 200°F, and if a stream contacts ion-exchange resins during cleanup, the maximum permissible temperature is limited to 140°F. The higher temperature streams are most often associated with return to the reactor primary system. Actually, much of the filtration of streams in the radioactive waste treatment system is done at ambient temperature.

(7) Pressures on the process streams at nuclear power plants range from atmospheric to 200 psig. The one exception is the coolant-pump-seal injection line which requires pressures around 3000 psig.

(8) Physicochemical characteristics of a treated stream may undergo change with changes in pH, temperature, pressure, or adulterants. The introduction of complexing agents may change the solubility of a species or alter its ionic form, and hence its physicochemical behavior. The addition of flocculating agents can form agglomerates of fine difficult-to-filter or unfilterable particulates, thus making their removal by filtration easier or possible.

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(9) Filter performance is measured by its ability to remove and hold solid stream contaminants; by the amounts of solid, liquid, and gaseous wastes it generates; by its ease of operation; by its maintenance requirements; and by the radiation exposures it causes during operation and maintenance. Filters used in nuclear power plants are changed most often on the basis of pressure drop (ΔP) across the filter or because the radioactive dose rate (R/hr) of the filter reaches a predetermined upper limit.

(10) Decontamination factor, although a measure of filter performance, is not usually monitored and is rarely, if ever, a determining factor for terminating a filtration cycle. The DFs gleaned from the data reported on filters (and not filter/demineralizers) ranged from 1.1 to 10 for gross β-γ activity and 1.6 to 2.5 for specific nuclides. The number of observations, however, is too scanty to allow statistical evaluations of and confidence to be placed on these numbers.

This review of the applications of filters in nuclear power plant operations has pointed up several areas that would benefit from further study and research. For instance, larger efforts to characterize the liquid streams at LWRs are needed if filtration is to be used more effectively. In particular, studies to provide more information on the amount of suspended solids in a stream and to determine the particle parameters (e.g., size distribution and shape) of these solids are required if rational correlations between the stream, a filter, and the processing variables that can be controlled are to be made. More tests, with feed that closely resembles the actual feed, carried out in a manner (e.g., successive batches or continuous) and under conditions (temperature, pressure, flow per unit area of filter medium, etc.) that simulate as closely as possible those of the large-scale operation being modeled, would be helpful. Since there is no generally accepted standard method for rating filters in either the filter or nuclear industries, and since sufficient operational experience is absent, meaningful comparisons of the expected performance of filters are difficult. Evolution

of a standard filter-test method that is not difficult, time consuming, or expensive and which is generally applicable to all filters would eliminate much of the confusion surrounding filter ratings.

2. BACKGROUND

The purposes of this study were to collect, collate, and report information on the performance of filters for radioactive liquids in light-water-cooled nuclear reactor (LWR) power plants. Information collected includes characterization of streams filtered, types of filters used, operating parameters, the efficiency with which radionuclides are removed from the stream treated, the characteristics and amounts of waste solids generated, and radiation exposures due to filters, as well as a comparison of design specifications and operating performance. The results of [illegible] provide operating data to assist the Nuclear Regulatory Co[illegible] and the nuclear power industry in their evaluation of the [illegible] of filters used in liquid streams at nuclear power plants. In a[illegible]se, the results are needed to evaluate the role of filtration [illegible] the radioactivity in the liquids discharged from any nucle[illegible]ion.

In LWR nuclear power p[illegible] liquid streams have various amounts of dissolved plus suspended s[illegible]d 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)[1] of the activated corrosion products (especially iron and nickel) tend to be present as suspended solids,[1-3] and fission products tend to be present dominantly as soluble forms. The development of facilities and equipment to collect and process radioactive streams has given the nuclear industry the capability to hold releases of radioactive material in liquid effluents within applicable regulatory limits. These limits are most readily met by reducing 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 filtration, evaporation, and ion exchange. Used to a lesser extent are centrifugation and reverse osmosis. Surveys similar to this one on filtration are given in refs. 4 and 5 on the use of evaporation and in refs. 6 and 7 on the use of ion exchange in LWR plants.

As a part of this study, a number of installations were contacted to obtain performance data on filters used to treat liquid streams at pressurized water reactor (PWR) and boiling water reactor (BWR) plants. They included 44 operating nuclear power plants or stations (representing 37 PWRs and 25 BWRs), 31 plants under construction (representing 51 PWRs and 21 BWRs), 14 filter vendors, 4 nuclear-steam-supply-system (NSSS) vendors, and 12 architect-engineers. A review of the published literature was done with emphasis on the treatment of liquids containing radioactive particulate solids comparable to those in LWR plants. Fundamentals of filtration were considered to facilitate the technical assessment of the data gathered in the study.

A characterization of the streams normally treated by filtration and the requirements put on the filters at LWR plants are presented in the next section.

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3. LIQUID STREAMS FILTERED AT LWR PLANTS AND FILTER REQUIREMENTS

For the most part, the liquid streams which are filtered at PWRs are different from those at BWRs. There are some streams, however, that both types of plants have in common although their chemical characteristics may be somewhat different. The requirements put on filters in LWRs due to temperature, pressure, flow rate, solids loading, and particle retention are not different from those in any other industry employing filters. On the other hand, the requirements put on by radioactivity (viz., shielding and remote operation) are different and pose a major constraint in the selection of filters for use in LWRs. The LWR streams filtered and the filter requirements are considered in more detail below.

3.1 Pressurized Water Reactors (PWRs)

In the primary system of a PWR, filters are generally used for treating any or all of several streams: the reactor coolant (letdown), chemical and volume control (reagent purification and coolant makeup), boron recovery, evaporator condensates (recycled for feedwater), and liquid radioactive waste (radwaste). In the secondary system of a PWR, filtration may be used to treat steam generator blowdown system condensate prior to discharge or recycle.

Filters are also used frequently in conjunction with ion exchange, the combination thereby removing both suspended solids and soluble ionic species from the treated stream. A filter may either precede or follow an ion-exchange bed in any stream so processed. In the pre-ion-exchange application, suspended solids are prevented from fouling the ion-exchange bed, thus increasing the operational efficiency of the bed. In the post-ion-exchange application, the filter serves to remove resin fines from the stream exiting the ion-exchange bed, thus preventing a troublesome widespread distribution of resin particles.

Reactor coolant purification is performed on a stream which has been depressurized (letdown) from system operating pressure and cooled to 140°F or below. The pressure of the letdown stream is usually in the

range of 100-200 psig, and the normal flow rate of the stream is between 30 and 150 gpm with suspended solids concentration ranging from <0.01 to 1 ppm. Particle-size distributions determined for the suspended solids found in PWR coolants during operation, and also the effects of reactor shutdown on these solids, are illustrated in Fig. 1. It is interesting to note that the standard deviation in all cases is the same, namely 2, although the median particle sizes in the specimens range from 1 to 4 μm. In addition, the particle size where the largest number of particles occurs (the mode) is about 0.5 μm in one case but is nearly five times as large in another, that is, 2.5 μm. These particle parameters are summarized in Table 1. Generally, after ion exchange the coolant letdown stream is passed through a purification filter before transfer to a makeup tank. This filter may be rated to handle a flow of up to 200 gpm or more and a pressure up to 200 psig with 95 to 98% retention of particles in the size range of 1 to 25 μm and larger. In some PWR plants a pre-ion-exchange filter similar to the post-ion-exchange filter is used in the reactor coolant purification stream. In this case, the filter is used to remove suspended solids or crud which is often released in spurious quantities (bursts) when changes occur in the reactor coolant pH or flow rate (i.e., reactor shutdown or start-up).[8-12] Similar observations have been made at BWRs.[13,14] A pre-ion-exchange filter in the reactor coolant purification stream may be required to withstand somewhat higher pressures than the post-ion-exchange filter.

The reactor coolant-pump-seal water injection (supply) and return filters are located in the chemical and volume control system of the plant. By using high-pressure pumps, makeup water from the chemical and volume control tank is forced through the seals of the reactor coolant pumps which circulate the primary coolant from the reactor core to the steam generator. While most of this makeup water flow enters the coolant loops, a portion of it returns to the makeup tank. The injection filters must handle between 10 and 300 gpm of solutio[illegible] pressures approaching 3000 psig and temperatures up to 250°F. To protect the reactor coolant-pump seals from damage, the suspended solids concentration must be very low (ideally <0.005 ppm), and the injection filters

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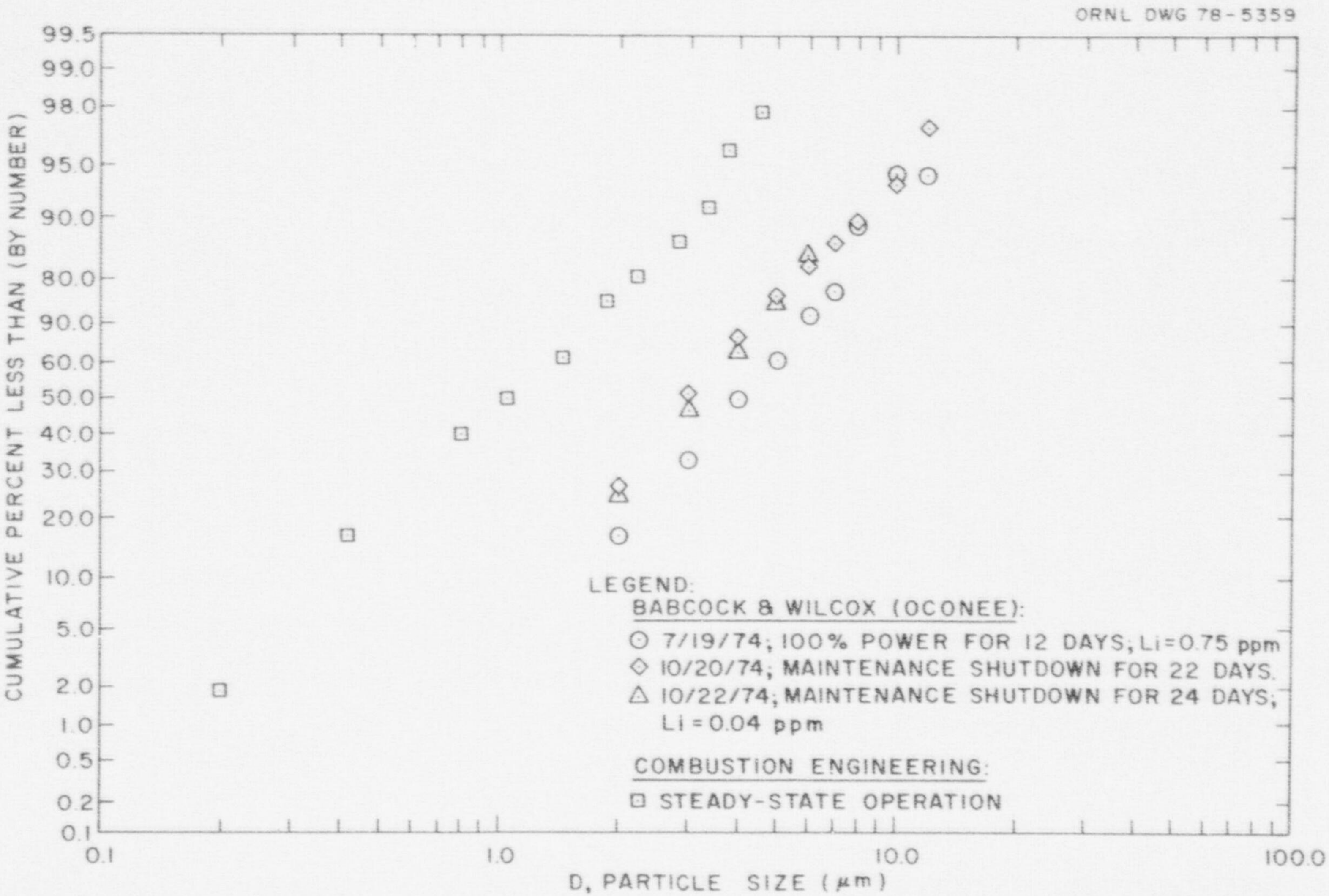

Fig. 1. Cumulative frequency of particles by number in PWR coolant plotted on logarithmic probability paper.

Table 1. Particle parameters based on numbers of particles determined[a] for crud in PWR primary coolant

NSSS Vendor	Particle Parameter (count basis)			
	Median (μm)	Standard deviation (dimensionless)	Mean (μm)	Mode (μm)
Babcock & Wilcox (Oconee)				
Shut-down[b]	3	2	3.8	1.9
100% power[c]	4	2	5.1	2.5
Combustion Engineering				
Steady state	1	2	1.3	0.6

[a]Determined from the data plotted on logarithmic probability paper in Fig. 1 and the relationships listed below:

Median = value at 50% probability;

Standard deviation (σ) = ratio of value at 84.13% probability to that at 50% probability;

Mean = median $\times$ exp $[\frac{1}{2} (\ln \sigma)^2]$; and

Mode = median $\times$ exp $[-(\ln \sigma)^2]$.

[b]After 22 and 24 days shut-down; Li = 0.04 ppm on 24th day.

[c]On 12th day of uninterrupted full power operation; Li ≈ 0.7–0.8 ppm.

must retain particles down to 10-µm size or, preferably, those as small as 5-µm size. The requirements for the return filters are not as stringent [the pressures are substantially lower (i.e., 100-200 psig), and the flow rates are usually smaller (i.e., 2-40 gpm)]. A minimum particle-size retention of 25 µm is sufficient in most systems.

In boron recovery subsystems, borated water from the reactor coolant system, including shim bleed, water arising from refueling operations, excess water due to thermal expansion, etc., is processed by evaporation and reused in a subsequent cycle. Filters are used extensively in such boron handling systems. Frequently the feed to the boric acid evaporator is pumped at <200 psig pressure through a filter having a 25-µm particle retention rating. This stream is usually at ambient temperature, and the flow rate is normally about 25-35 gpm. The condensate from the boric acid evaporator, which may contain up to 100 ppm of suspended solids, is filtered before storage and subsequent reentry into the makeup system. The temperature of the evaporator condensate may approach 165°F, and ratings required for such filters are 250°F, 200 psig, and retention of 25-µm size particles. The evaporator concentrates containing

up to 12% by weight boric acid are maintained at elevated temperatures to prevent solidification in the evaporator and transfer lines. These concentrates are filtered enroute to the boron recycle storage tanks. The filters used in this application are rated for temperatures and pressures as hign as 250°F and 150-200 psig, respectively. The particle retention ratings vary from 2-75 μm, since the boric acid is filtered again before being metered into the reactor coolant system. Transfer of boric acid evaporator concentrates is normally a batch operation, and flow rates can be in the 40- to 100-gpm range.

The liquid radwaste systems of PWRs are not standardized and therefore generalization is somewhat difficult. However, most plants do identify miscellaneous wastes deriving from the primary system cleanup, equipment drains, floor drains, and sampling systems; chemical wastes, which include those from laboratory drains, chemical cleaning, and decontamination operations; resin bed regenerants; and detergent wastes from laundry and personnel showers.[15] Suspended solids in the miscellaneous waste stream are frequently as high as 250-1000 ppm. Detergent wastes are described in Sect. 3.3 where streams common to BWRs as well as PWRs are discussed. A generic diagram of the liquid radwaste processing system for PWRs, showing some of the appropriate applications of filters, is presented in Fig. 2. Nearly all PWR liquid wastes are filtered prior to ion exchange, which precedes discharge or solidification. The feed to a waste evaporator may or may not be filtered depending upon the design of the waste evaporator. Where evaporation is used, filtration may be performed on the condensate prior to discharge rather than on the feed. The specific treatment chosen for any waste stream is dependent upon both the solids content and the level of radioactivity in the stream. For low activity-level wastes, filtration may be the only processing required before discharge. Streams with high levels of radioactivity and low solids contents can usually be handled by ion exchange alone. Wastes with high activity levels and/or high total (suspended plus dissolved) solids concentrations may be evaporated and the condensate filtered prior to recycle or discharge. For radwaste applications, filter specifications usually call for up to 200 psig pressure, up to

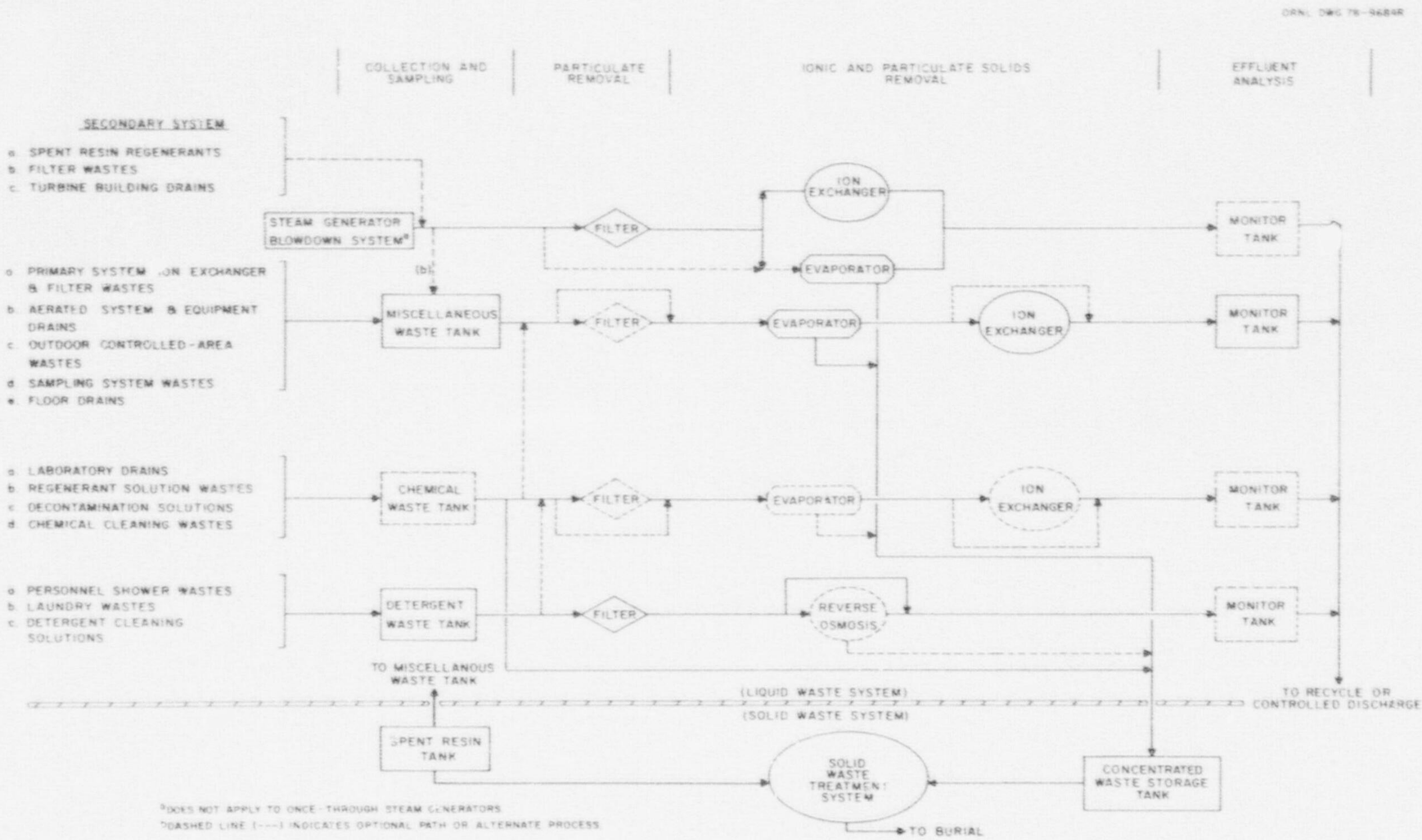

Fig. 2. Flow diagram of a basic liquid radioactive waste processing system for a PWR. (Taken from American National Standard N199-1976/ANS-55.2).

250°F temperature, flow capacities of 40-150 gpm and 1- to 25-μm particle-size retention.

In the secondary system of a PWR, steam generator blowdown water may be filtered either before or after demineralization. A cooling condenser may be used to reduce the blowdown temperature to <150°F and pressure to atmospheric or less. Flow rate from the condenser is 50 to 125 gpm. A retention rating of 3-μm particle size is usual for these filters. The spent ion-exchange resins arising from steam generator blowdown treatment may be dewatered using a filter.

3.2 Boiling Water Reactors (BWRs)

In BWRs, filtration is usually performed in the reactor coolant cleanup, feedwater, and radwaste systems. Most plants segregate their liquid wastes into high-purity, low-purity, chemical, and detergent wastes.[16] Of these, only the chemical wastes, which derive from ion-exchange resin regeneration, laboratory drains, and nondetergent decontamination operations, are normally not filtered prior to evaporation and solidification. The detergent wastes are discussed in Sect. 3.3, which describes waste streams that are common to BWRs and PWRs. A generic diagram of the liquid radwaste processing system for BWRs, showing some appropriate applications of filters, is presented in Fig. 3. Also, filtration and ion exchange with powdered resins as a single combined unit operation (i.e., filter/demineralizer units) will not be covered here. A discussion of these waste purification systems is presented in refs. 6 and 7.

The reactor coolant cleanup stream in a BWR, just as in a PWR, is purified by filtration plus ion exchange and, as in a PWR, is cooled down (generally, to about 90-120°F) before treatment. Unlike the PWR counterpart (letdown stream), the BWR coolant cleanup stream is maintained at the reactor system pressure of 1000-1200 psig (or higher) since it is injected back into the reactor immediately following purification. The suspended solids feed concentration is the range of 0.01-5 ppm, which is slightly higher than that of PWR coolant cleanup streams. The BWRs using deep-bed ion exchange for coolant cleanup have substantially

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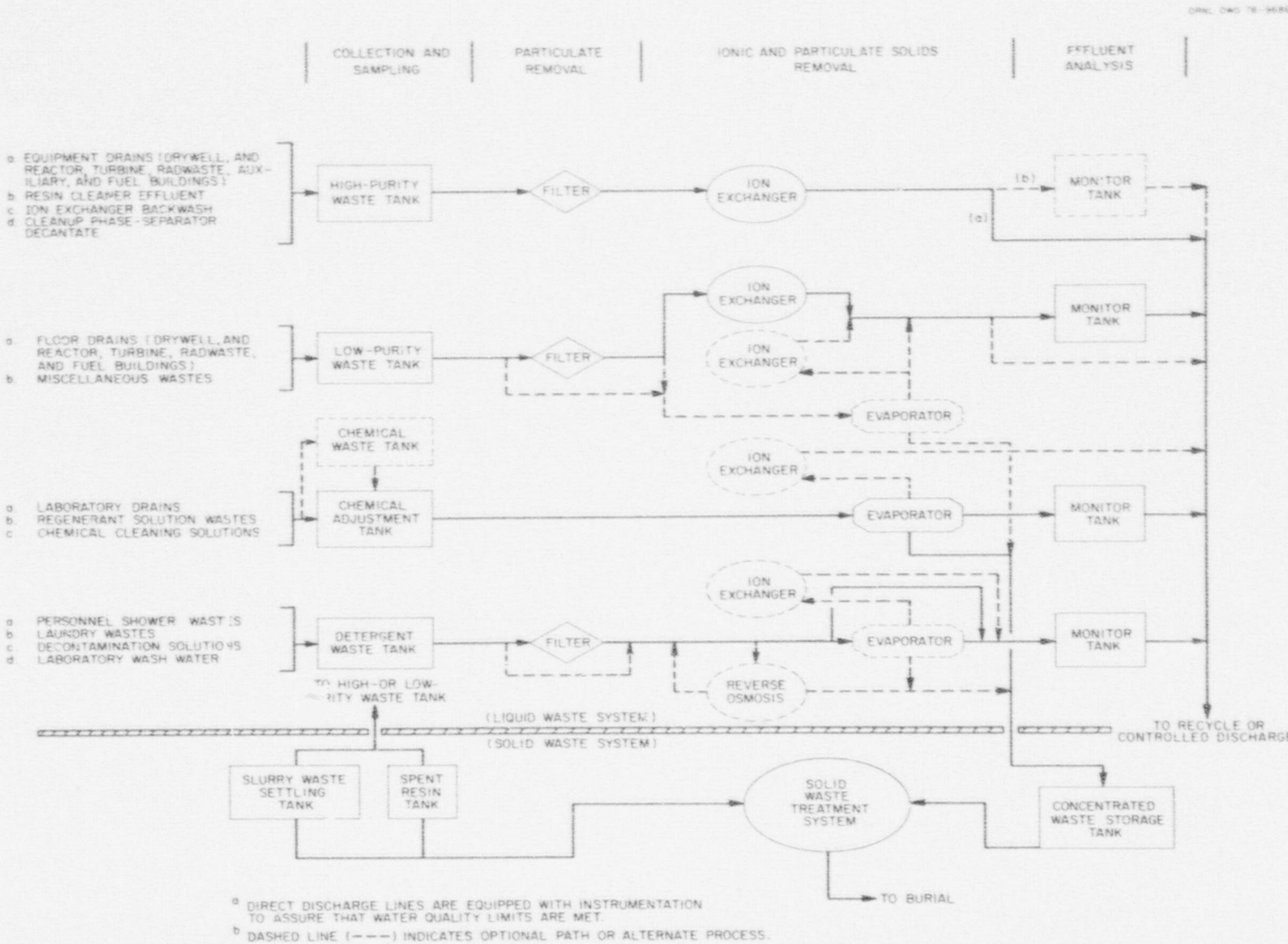

Fig. 3. Flow diagram of a basic liquid radioactive waste processing system for a BWR. (Taken from American National Standard N197-1976/ANS-55.3).

higher flow rates for this stream than do plants using powdered resin (combined filter/demineralizer) units; i.e., 700-1100 gpm vs 70-180 gpm, respectively.

The condensate returning to the reactor from the steam turbine contains 0.005-0.015 ppm of suspended solids and is also treated by filtration and ion exchange before reentry to the reactor. To prevent damage to the resins, the temperature is lowered to about 100-125°F; the pressure is normally in the 300- to 700-psig range. The condensate flow rate is several thousand to tens of thousands of gallons per minute, and multiple purification units are frequently used. A flow rate in the order of 2500-3000 gpm per unit is common.

The high- and low-purity waste streams at BWRs are collected separately, but their treatment is essentially the same. Both these types of waste are filtered prior to further treatment by ion exchange before either recycle within the plant or discharge to the environment. If the low-purity waste stream becomes too high in dissolved solids concentration to be processed by ion exchange, it may or may not be filtered before evaporation and subsequent solidification.

The high-purity or clean wastes are low-conductivity wastes that arise mostly from drywell and reactor, turbine, and radwaste building equipment drains, and reactor cleanup systems. These high-purity wastes are routed to a waste collection tank and from there may be processed either continuously or batchwise. The stream exiting from the waste collection tank is normally pH 6-9, at ambient temperature, and at an operating pressure in the range of 50-110 psig. The suspended solids in this stream can vary from 3 to 200 ppm. Flow rates are usually about 60-200 gpm but may be as high as 400 gpm at large BWR plants.

The low-purity or dirty wastes are high-conductivity wastes that arise mainly from floor drains in the reactor, turbine, and radwaste buildings. Like the high-purity wastes, they are routed to a separate waste collection tank from which they are processed either continuously or batchwise. The stream exiting the low-purity waste collection tank is similar to that for the high-purity waste except that, in general, the flow rate is somewhat lower, i.e., from less than 20-150 gpm. The

normal suspended solids concentration in this stream prior to filtration is 70-500 ppm, but on occasion it may be as high as 1500-2000 ppm.

3.3 Streams Common to Both Types of Reactors

The PWRs and BWRs have two similar (although chemically different) streams, namely, the spent fuel pool cleanup and detergent streams.

In the spent fuel pool (and refueling canal), surface dirt is often removed with a skimmer that may contain a filter. Since it is desirable to keep the radioactivity level as low as readily achievable to minimize radiation exposures, a combination of filtration and ion exchange is usually used in this recirculating stream. The temperature of the fuel pool water may be around 100°F (but no higher than 140°F), and the flow rate may be 400-800 gpm or more. The suspended solids in the fuel pool may range from less than 10 ppm up to 300 ppm, depending upon the operations being performed in the pool. The usual particle-size retention rating for fuel pool cleanup filters is in the range of 1-25 μm. Some plants treat their refueling water separately but in a similar way.

The detergent wastes from laundry, personnel showers, and other decontamination activities are usually high in solids content (100-200 ppm) but very low in radioactivity (dose rate of a few mR/hr). The high solids content of laundry wastes (viz., lint) sometimes causes rapid fouling of filters used for these wastes. However, normally, these filters do not become so radioactive that remote handling is required, so for this stream, both PWRs and BWRs tend to use disposable filters with no further treatment prior to discharge. The flow rate of the detergent waste stream is usually <50 gpm, and a filter having a minimum particle-size retention in the range of 3-25 μm is most often employed. When a plant is designed for "zero-release" of liquid wastes, detergent wastes may be treated by a combination of filtration, evaporation, ion exchange, and/or reverse osmosis (see Figs. 2 and 3) and the recovered water recycled.

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4. GENERAL DESCRIPTION OF FILTERS FOR LIQUIDS IN LWR PLANTS

Liquid filtration, as used in this study, consists of mechanically separating a mixture of suspended solids and liquid with a porous body (filter medium) which permits the liquid to flow through while retaining the solids on or within itself. The solids-liquid mixture is called feed slurry or prefilt, and the liquid that passes through the filter medium is called the filtrate. Basically, filtration is the flow of fluid through porous media. The flow is always induced by some driving force (e.g., gravity, pressure, or vacuum). If essentially all the solid particles removed are entrapped within the initial filter medium, rather than upon it so that a visible film or layer appears, the process may be referred to as filter-medium filtration, examples of which include micronic filtration, clarification, and ultrafiltration. If the initial filter medium supports the particles removed in the form of a porous layer, which retains more of the solids present in the slurry and thus adds successive layers, the process is commonly called cake filtration. The filter cake, once it begins to form, acts as a filter medium. Numerous other terms such as depth filtration and surface filtration, which are defined in the Glossary (Sect. 10), are used to classify filters by mechanism.

In filter-medium filtration, the initial porous body remains the primary filtering agent throughout filtration; whereas, in cake filtration, the initial porous body (a thin cloth, screen, or membrane referred to as an initiating medium) starts the formation of a filter cake which then becomes the filter medium. Initiating media may be divided into "depth" and "surface" groups to describe the early stages of cake formation. If suspended solids can penetrate some distance into the porous material (passing along large pores, but being eventually entrapped in one of the smaller pores) during the time that the first layer of cake is forming on the surface, the material can be termed a depth-initiating medium. Some examples are matted fiber and porous ceramics. On the contrary, if the particles do not appreciably penetrate the material during cake formation, the material can be termed a surface-initiating

medium (e.g., a membrane). A surface-initiating medium is characteristically one with a narrow distribution of pore sizes and shapes with a relatively well-defined, straight, liquid flow path (a low tortuosity) between the upstream (prefilt) surface and the downstream (filtrate) surface of the medium, while a depth-initiating medium is the opposite. Obviously, a wide range of material lies between these bounds.

Problems with slow filtration rate, rapid medium clogging, unsatisfactory filtrate clarity, and difficult cleaning of the medium at the end of a cycle may be mitigated by the use of filter aids. These are granular or fibrous materials capable of forming a highly permeable filter cake on or within which solids from the prefilt will be trapped or incorporated. Filter aids are used in two ways. In the first, called precoating, the initial filter medium is coated with a thin, porous cake of the filter aid before filtration begins. In the second, called body feeding, the filter aid is mixed with the prefilt and the mixture is fed to the filter. Both precoat and body feed may be used in a given filtration. More fundamentals of liquid filtration are presented in Appendix A.

Numerous methods have been devised for evaluating filter media. Several of these methods and a few widely accepted standard contaminants tha have been used in testing filter media are described in Sect. 5 and Appendix A.

Filters of various types are widely used throughout the different systems of nuclear power plants to remove suspended solids from liquid streams that are to be recirculated (recycled) within or discharged from the plant. The need for removal of these solids may stem from requirements for low radioactivity level or freedom from unwanted (interfering and abrasive) materials as brought out by the description (Sect. 3) of streams that are filtered. For example, radioactive suspended solids may be removed from a stream to reduce the level of radioactivity so that it can be recycled within the plant or discharged to the environment (e.g., laundry wastes). Occasionally, the suspended solid represents a material of value whose recovery is desirable (e.g., resin slurries). Often, suspended solids are removed because they can interfere

with a subsequent operation or process (e.g., ion exchange or evaporation). Frequently, they are removed to prevent their abrasive attack on equipment and instruments located downstream.

Filtration and filters may be categorized in a number of ways, several examples of which are given in Appendix A, depending usually upon the classifier's interest. Since the characteristics and amounts of solid radwaste generated by filters are among the prime interests of this study, a division that seems to bring out these points has been selected. The many types of filters that have been used for liquids in nuclear power plants have been roughly divided into two main categories: disposable and reusable. Under each of these main categories, several types of filters are included. Those types which are in use or are proposed for use in nuclear power plants are described in the following sections.

4.1 Disposable Filters

Two generic types of disposable filters are in use at nuclear power plants today. The most widely used includes the many varieties of cartridge-type filters employed in process stream cleanup at PWRs. The bag-type filter is in use in the sludge intercept system in at least one PWR (Kewaunee).

4.1.1 Cartridge filters

Disposable cartridge filters contain from one to several replaceable elements which are discarded when they become contaminated or loaded to the extent that either the radioactive dose rate or the differential pressure (ΔP) across the filter reaches a preset value. In nuclear power plant applications, multiple elements are often mounted in a single removable supporting structure and, to minimize radiation exposure, the entire assembly is discarded at changeout.[17] Some disposable elements used in nuclear power plants have filter media of woven fabric, wound fiber (string), or pleated paper, supported on a rigid inner core of perforated stainless steel as shown in Fig. 4. For this type of element, the liquid flow is from outside to inside. There are also

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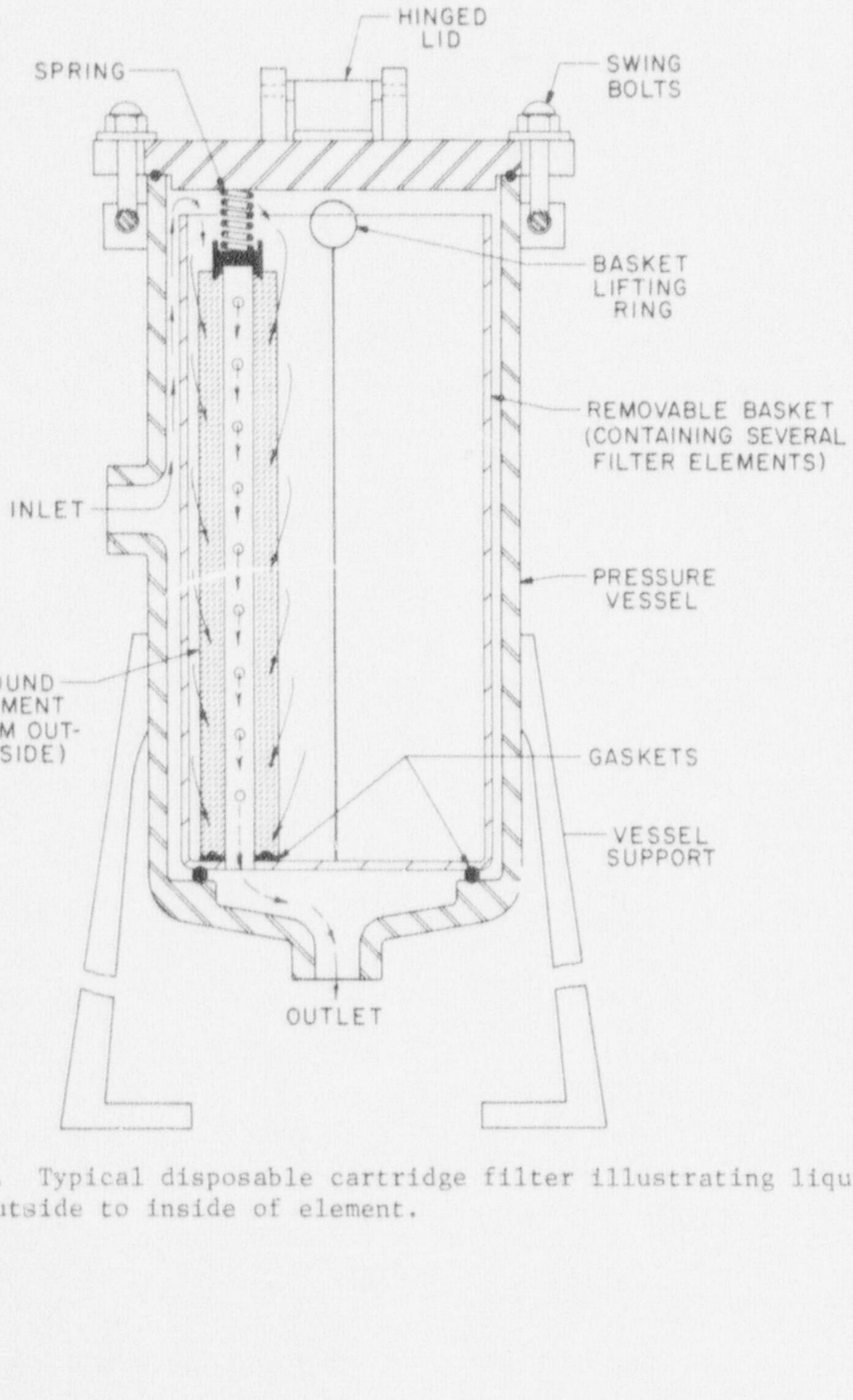

Fig. 4. Typical disposable cartridge filter illustrating liquid flow from outside to inside of element.

pleated or matted paper elements that are externally supported by a stainless steel basket to accommodate fluid flow from the inside to the outside of the element as shown in Fig. 5. In this case, the solids removed can be contained within the supporting basket should the cake be sloughed off due to interruption of flow.

Cotton, nylon, and epoxy-impregnated paper are among the materials commonly used in fabrication of disposable cartridges for nuclear power plants. These cartridges are available in pore sizes ranging from one micrometer up to several hundred micrometers. A short guide useful in the selection of cartridge (and other) filters is presented in Table 2 (a longer one is given in Table A-1 of Appendix A).

For the most part, disposable cartridge filters perform well in removing suspended solids from the process streams of nuclear power plants. Difficulty of remote changeout is probably their greatest shortcoming[18-20]

4.1.2 Bag filters

Nylon mesh bag filters are used at Kewaunee in conjunction with disposable cartridge filters in the sludge intercept part of the radwaste treatment system. The bags are located in the low-temperature, low-pressure transfer line connected to the miscellaneous waste settling tank; disposable cartridge filters are also located between this tank and the waste collection tank. The bags are housed in a vessel of approximately 6-in. O.D. by 8-in. length, and the nominal minimum particle size retention is 15 μm. The filters are changed manually on the basis of pressure drop or dose rate. A typical bag filter is illustrated in Fig. 6. Experience with bag filters in nuclear power plant applications is not sufficient at this time to characterize them more fully.

4.2 Reusable Filters

There are several types of reusable filters. Of the backflushable variety, there are some that do not require precoat and some that do. The backflushable filters usually employ a reversed flow (bump) of air

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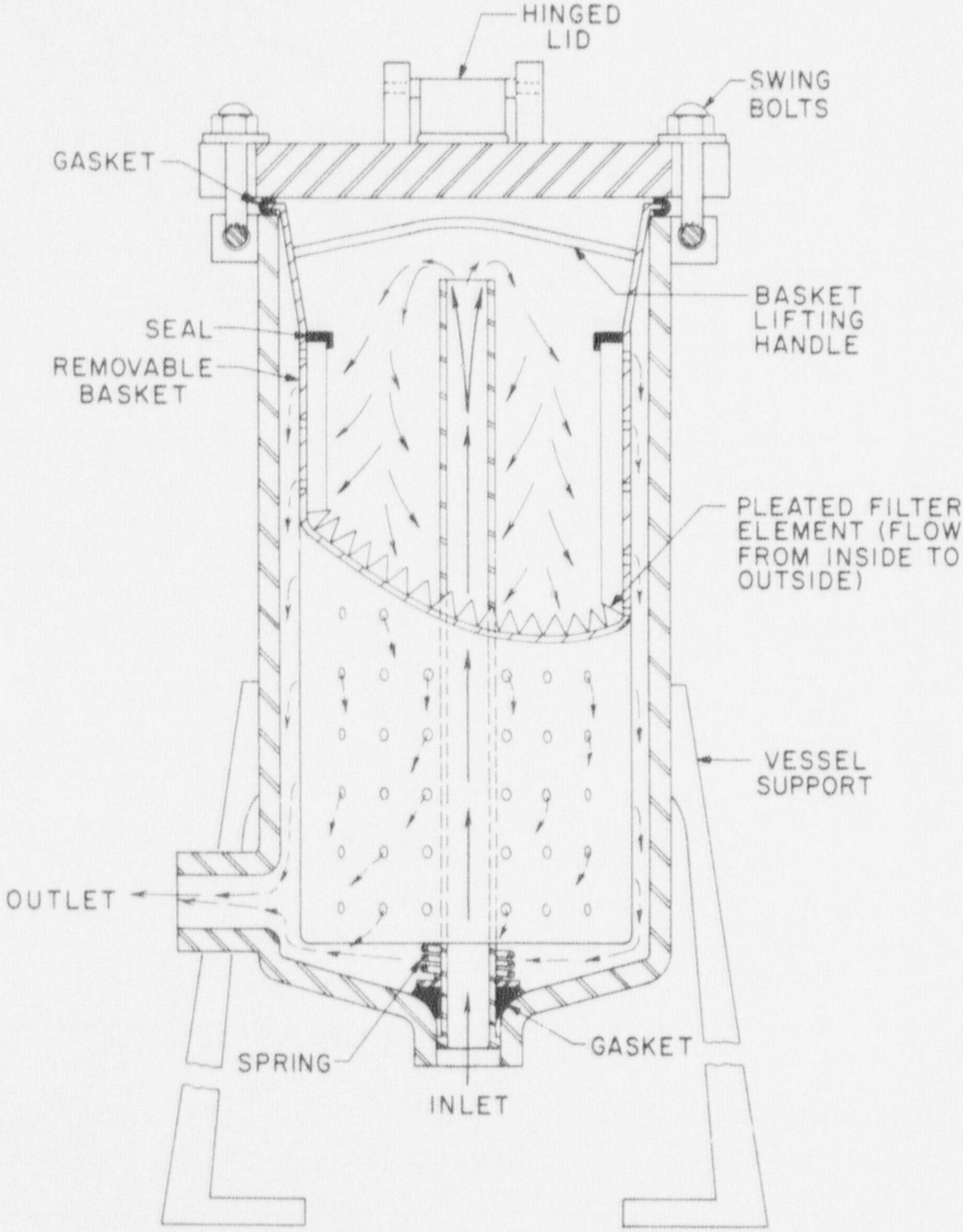

Fig. 5. Typical disposable cartridge filter illustrating liquid flow from inside to outside of element.

Table 2. A particle retention[a] rating guide useful in the selection of filters

(Based on AMF Cuno brochure, "Industrial Filters," GI.20.5, issued 2-15-77)

Purpose	Minimum particle size[b] to be retained
To remove minute, visible "specks"	A 40- or 50-µm filter should be specified.
To produce optical clarity in a liquid	A 25-µm or finer rating is needed.
To remove a "haze" from a liquid	A 10-µm or finer filter will probably be needed.

[a]The term "micron" (µ), a millionth of a meter, though still commonly used throughout the industry, is being replaced with "micrometer" (µm), a millionth of a meter.

[b]As an aid in determining the required degree of filtration, the following comparisons give an idea of approximate µm sizes:

One µm = 0.0000394 in.
A single grain or particle of cocoa, talcum, or face powder is 5 to 10 µm.
The average lower limit of human sight is 30 to 40 µm.
The average diameter of human hair is 50 to 70 µm.
A single grain of table salt is approximately 90 to [illegible] µm.

or nitrogen followed by clean filtrate or process water to push the accumulated cake from the initiating medium and transport it to a sludge storage tank. The reusable precoat filters that discharge dry cakes rather than slurries depend largely on mechanical devices for cake removal, thus minimizing the amounts of backwash liquid that might be needed. However, cake drying requires a gas (usually air) that may need treatment prior to release. Most of the reusable filters in use at nuclear power plants are readily adaptable to automatic remote operation.

4.2.1 Filters without precoat

There are several types of backflushable filters in use at nuclear power plants that do not require precoats to affect the solids-liquid separation. These filters are backflushed and used again and again until eventual plugging of the initiating medium forces discard. Some of these nonprecoat filters can be cleaned thoroughly and are expected to be reused throughout the life of a plant.

4.2.1.1 Porous metallic filters. Backflushable porous metallic cartridges are made of woven wire or sintered metal with many variations obtainable in the 5- to 10-µm pore size range. Since backflushing does not completely remove fine particles that lodge in the filter medium pores during filtration, woven wire and sintered metal elements are best

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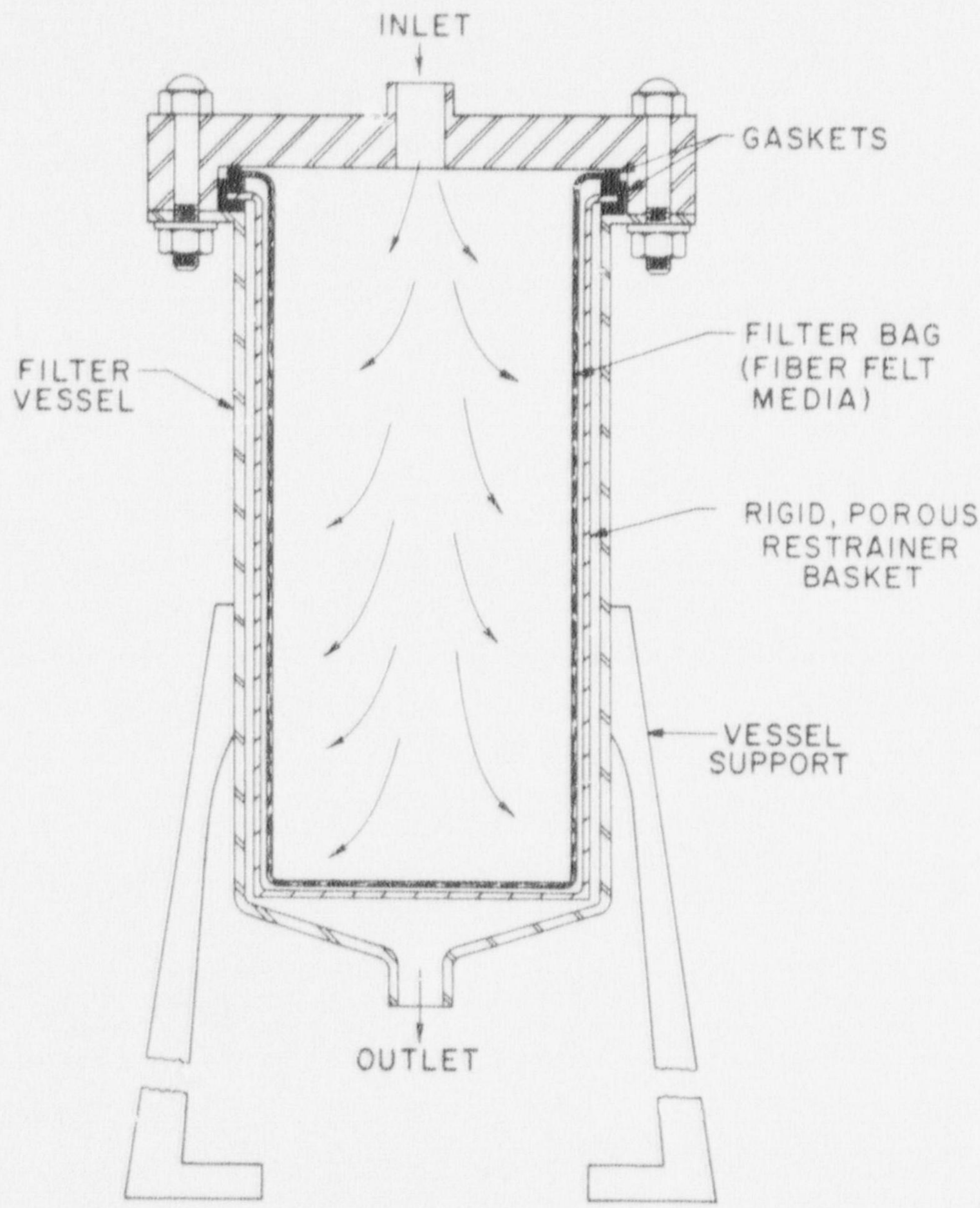
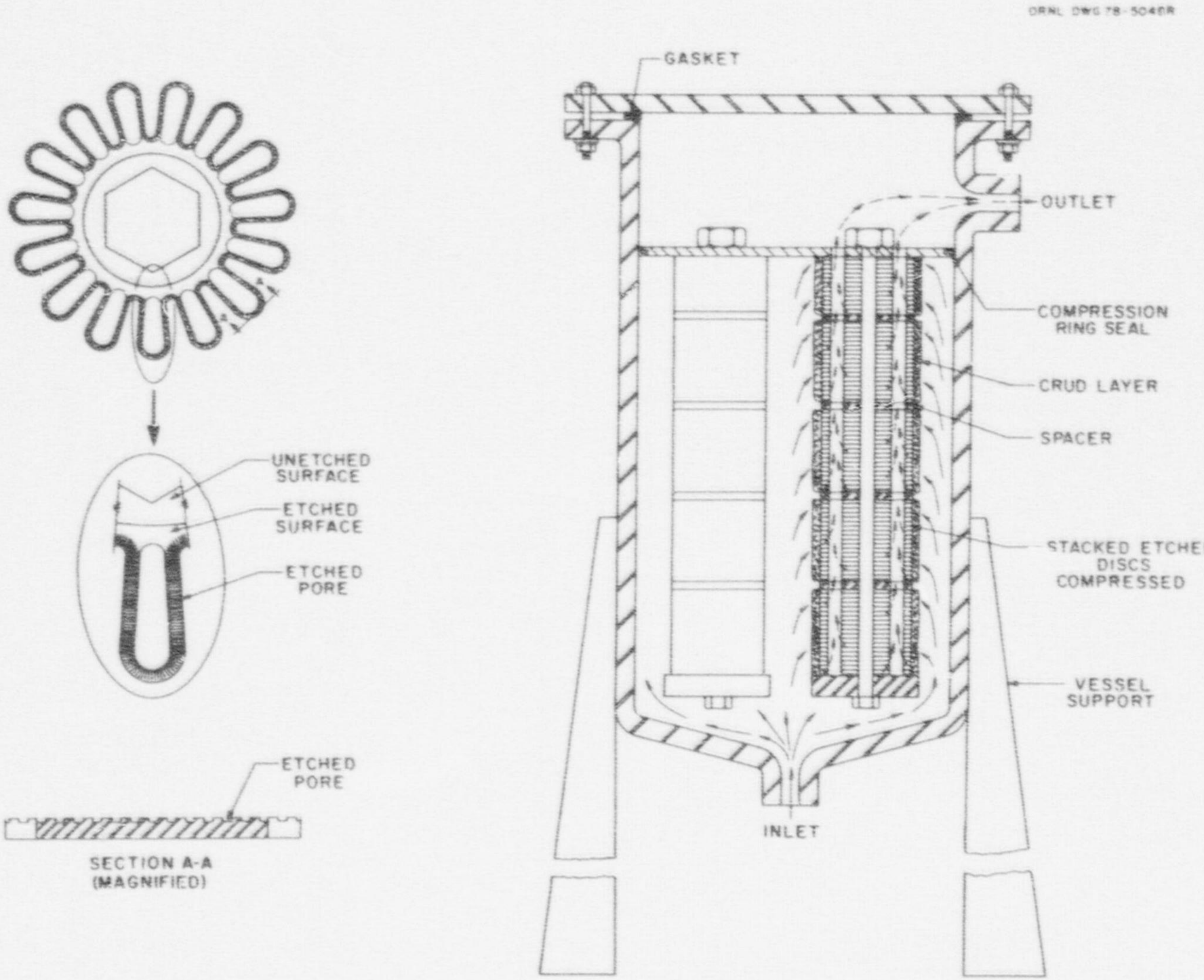


Fig. 6. Typical disposable bag filter.

suited to removal of larger-sized particles. The use of harsh cleaning solutions for the purpose of dissolving entrapped solids may result in chemical attack on the filter itself, with consequent erosion of its structural integrity.

4.2.1.2 Porous ceramic filters. Backflushable porous ceramic cartridges are being used in at least two PWR primary systems. Backflushing is done with water or a suitable cleaning solution. At San Onofre 1, this type of filter is used in the primary coolant cleanup system where 98% retention of solid particles down to 25 μm is specified. The plant also has this type of filter in the coolant-pump-seal injection and return line. Maine Yankee also uses a similar filter on the coolant-pump-seal injection and return line. At Maine Yankee, the particle retention specification is 95% for particle sizes down to 7 μm. Depending upon the type of ceramic, porous ceramic filters can be used at temperatures as high as 1000-2000°F.[21]

4.2.1.3 Stacked etched-disc filters. The etched-disc filter (see Fig. 7) is a closed pressure vessel containing elements made of vertically mounted stacks of chemically etched stainless steel discs which are tightly compressed by mechanical means. The discs are etched on one side only and are stacked with all the etched surfaces oriented in the same direction. In this way, open slots of precise size (normally 5 μm) and shape are formed between each individual disc. Prefilt is pumped through the filter with the fluid flowing through the elements from the outside. As a layer of solids builds up on the outside of the elements, the pressure drop across the filter increases. At a preset ΔP, the feed is terminated and backflushing begins automatically with a bump of high pressure air or nitrogen followed by water. The backflushed gas and water are collected in a vented backwash holdup tank. The air or nitrogen may be directed to the plant off-gas treatment system prior to discharge. The waste slurry is solidified with or without evaporation. Normally, these filters are used without precoat, but for oil removal a precoat of diatomaceous earth may be desirable. The etched-disc filters proposed for at least one PWR plant now under construction (San Onofre 2 and 3)



(a) TOP AND CROSS SECTIONAL VIEWS OF ETCHED DISC

(b) ASSEMBLED ELEMENTS IN FILTRATION STAGE

Fig. 7. Views of etched disc and schematic of a typical etched-disc filter.

have this option. Run times are shortened by high solids loading, and frequent backflushes are necessary if the treated stream is high in suspended solids concentration.

4.2.2 Filters with precoat

Several types of precoat filters are in use in liquid radioactive waste treatment systems.[22-26] The most widely used types are the tubular-support pressure-precoat filters which discharge slurries. Precoat filters that discharge a dried cake include the flat-bed, centrifugal-discharge, and clamshell filters. In normal operation, precoat filters are efficient at removing particles as small as 1-μm size. Oils, which may be present in nuclear power plant liquid waste streams, are not removed unless diatomaceous earth precoat is used. Cellulosic materials (e.g., Solka-Floc) and powdered resins are not satisfactory precoat materials for oil removal. Furthermore, Solka-Floc precoat has frequently resulted in release of excessive fines from the filter medium. These fines can cause problems with (i.e., shorten the life of) ion-exchange beds downstream. When powdered resin precoat is used, the temperature must be kept below 140°F to prevent resin decomposition. The large volumes of sludge produced by precoat filters may be their greatest drawback. On the other hand, the greatest advantage of precoat filters is the ease with which they lend themselves to automatic and/or remote operation, greatly reducing radiation exposures under normal circumstances.

4.2.2.1 Vertical pressure-tube filters. Among the many types of precoat filters that discharge a moist sludge, tubular-support pressure-precoat filters have apparently been the ones most used in nuclear power plant service. In precoat filters of these types, porous, vertically mounted, tubular elements support and retain the filter medium, as shown in Fig. 8. The precoat layer is formed by passing a slurry of such material as diatomaceous earth, Solka-Floc, or powdered ion-exchange resin through the tube bundle before filtration begins. Suspended solids in the feed stream are caught in and on the precoat layer, and

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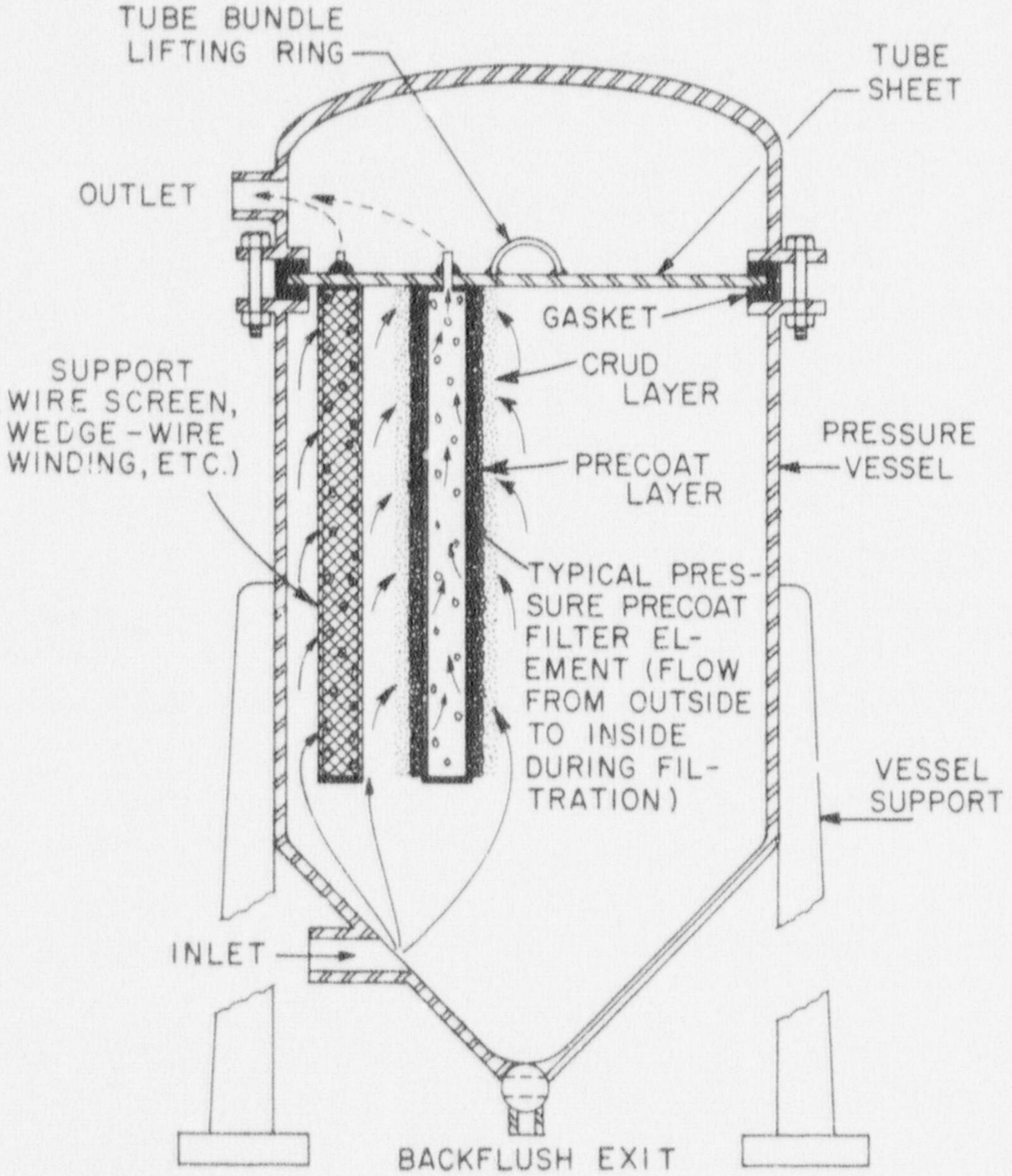

Fig. 8. Typical tubular-support pressure-precoat filter.

gradually, the filter cake thickens. As the cake builds, the differential pressure across the filter also increases until a preset value of ΔP is reached. If the concentration of suspended solids in the feed stream is especially high (i.e., several hundred ppm or more), small amounts of additional filter aid may be added to the feed. This body feed prevents clogging of the initial precoat by providing greater dispersion of the solids being removed throughout a thicker cake. This, in turn, prolongs the run length before the maximum ΔP occurs. At the point of maximum allowable ΔP, the backflushing process is initiated either automatically or manually. As with the etched-disc filters described in Sect. 4.2.1.3, the backflush usually begins with an air or nitrogen bump to loosen the cake. This is followed by a reverse flow of wash liquid that is routed to a sludge holdup tank. After the elements have been thoroughly cleaned, the precoat and filtration part of the cycle is resumed.

Maintenance of steady pressure and liquid flow are important in pressure-precoat filter operation, since fluctuations can result in uneven cake distribution or in loss of cake from vertically mounted elements.

4.2.2.2 Centrifugal-discharge filters. The centrifugal-discharge filter is a pressure-precoat filter in which the precoat and cake supports are wire mesh screens mounted on horizontal leaves attached to a hollow vertical shaft located at the center of the pressure vessel. A centrifugal-discharge filter is shown in Fig. 9. Dry-cake discharge is accomplished by rotating the central shaft at 200 to 300 rpm, which slings the solids against the vessel wall. The solids collect at the bottom where they are mechanically pushed into the discharge chute. Diatomaceous earth is the usual precoat material used in centrifugal-discharge filters. Cellulosic precoats (e.g., Solka-Floc), when used alone, tend to "bake" onto the wire screens during air-drying, forming hard coatings that are difficult, if not impossible, to discharge. Powdered resins by themselves tend to form unstable, uneven cakes. In dewatering cellulosic power plant filter sludges and spent demineralizer resins with a centrifugal filter, satisfactory performance can be achieved if sludge and resin are mixed in proper proportion.

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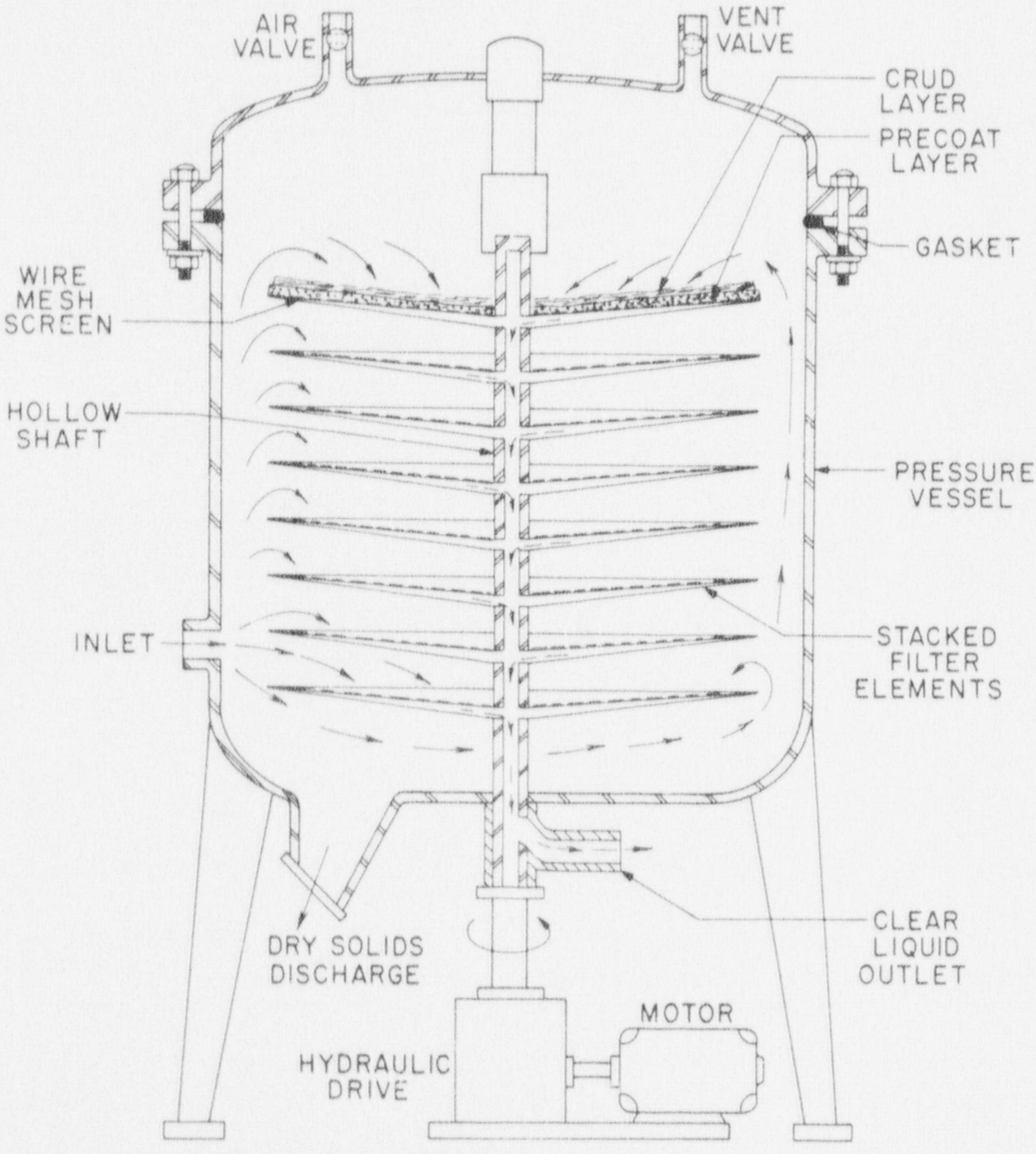

Fig. 9. Typical centrifugal-discharge filter.