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

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CONTENTS

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ABSTRACT

A survey was made to investigate the current and future use of evaporation 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, and architect-engineers, as well as evaporator manufacturers and vendors. Principal interest was placed upon obtaining operating data on the performance of evaporators used at LWR plants to treat radioactive liquid streams containing primarily (a) several tens to several thousand ppm of boron (pH of ∿4 to 10), (b) several tens to ten thousand ppm of boron plus several hundred to ten thousand ppm of sodium and ammonium sulfates (pH of ∿3 to 11), and (c) up to several ten thousand ppm of sodium sulfate (pH of ∿6 to 9).

Included in this report are characteristics of the streams evaporated at both pressurized water reactor (PWR) and boiling water reactor (BWR) plants and the evaporator requirements for these streams. The many types of evaporators used, or proposed, for treating radioactive liquids at LWRs are described. To facilitate the collation and interpretation of data, evaporators are categorized as natural circulation (NC), forced circulation (FC), spray film (SF), and submerged U-tube (SU). The majority of the evaporators in early PWR (for boron recycle and waste) and BWR (for waste) plants were of the NC and SU types. However, the majority of the waste evaporators in later plants (and early plants making replacements) are of the FC type.

Technical data collected include the type and number of evaporators used; materials of construction utilized; the kinds of ancillary equipment employed such as gas strippers, feed filters and preheaters, and mist separators; important operating parameters such as boil-off rate, pressure, and time; and results such as volume reduction and decontamination factor (DF) obtained. The results show that a mean system DF of about 10^4 can be expected for nonvolatile fission and corrosion products treated in single-effect NC and FC evaporators and of about 10^3 in SF and SU types. The mean system DF expected for iodine is about 10^3 in the NC and FC types and about 5×10^2 in the SF and SU types.

1. SUMMARY AND RECOMMENDATIONS

Operating and design data on evaporators were collected by direct contacts with 60 organizations including suppliers of nuclear-steam-supply systems, architect-engineers, evaporator 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 evaporation in reducing the releases of radioactivity to the environment from nuclear power plants.

Thorough characterization of the various streams normally treated by evaporation, in terms of the concentration of dissolved and undissolved solids (stable and radioactive), is rather limited although 46 plants representing 65 reactors were in operation (December 31, 1977). A limited amount of information on the system decontamination factor (DF), ratio of the amount of a constituent in the feed to its amount in the condensate, is available. The report includes a general description of evaporators used, or proposed for use, in LWR plants. In addition to a description of the streams treated and evaporators used, the basic theoretical and design factors influencing evaporator selection and performance are presented.

To facilitate the collation and interpretation of data (especially DFs), evaporators are categorized as natural circulation (NC), forced circulation (FC), spray film (SF), and submerged U-tube (SU). The results of this survey show that a mean system DF (as defined in Table 1) of about 10^4 can be expected for nonvolatile fission and corrosion products in the NC and FC types, while a mean system DF of about 10^3 can be expected for iodine. They further show that a mean system DF of slightly over 10^3 can be expected for nonvolatile fission and corrosion products in the SF and SU types, while a mean system DF of about 5×10^2 can be expected for iodine. These comparisons are summarized in Table 1. In addition, these results indicate that the waste evaporators in pressurized water reactor (PWR) and boiling water reactor (BWR) plants give similar DFs. However, they show that in PWR plants the boron recycle

Table 1. Comparison of mean system decontamination factors[a] by evaporator type[b]

Activity	Mean system decontamination factor			
	NC	FC	SF	SU
Gross β-γ	4E + 04	2E + 04	3E + 03	9E + 03
Iodine	1E + 03	2E + 03	3E + 02	7E + 02
FPs[c]	4E + 04	1E + 04	2E + 03	3E + 03
CPs[d]	2E + 04	1E + 04	3E + 03	3E + 03

[a] Instantaneous system decontamination factor $[(DF)_{si}]$ is defined as the ratio of the concentration for a given component in the feed at any time to the concentration for the same component in the condensate at that time. The means were calculated using the expression:

$$\overline{(DF)}_{si} = \frac{1}{n}\sum_{j=1}^{n} (DF)_{si} \ .$$

where
$\overline{(DF)}_{si}$ = the mean value of $(DF)_{si}$,
n = the number of observations, and
j = an integer.

[b] Evaporator types: NC = natural circulation; FC = forced circulation; SF = spray film; and SU = submerged U-tube.

[c] FPs = fission products.

[d] CPs = corrosion products.

evaporator can give DFs that are lower than those of the waste evaporator by a factor of up to 10.

While boron recycle evaporators have generally not posed any major problems, tube plugging, corrosion, and evaporator undersizing have been frequent problems with waste evaporators at PWRs. The use of larger diameter tubes and/or replacement of stainless steel with Inconel 625 in the tube bundle, as well as preventive maintenance via scheduled cleaning, are some of the remedial actions that have been used. Most plants have either modified their original, undersized evaporators to increase capacity and/or have augmented them by addition of another larger evaporator; however, a few in this circumstance have abandoned evaporation in favor of ion exchange with no resin regeneration. The stress corrosion problems experienced with waste evaporators, especially at BWRs, can apparently be solved by using Incoloy 825, Inconel 625, and/or

Alloy 20 as fabrication materials, and several plants now under construction are taking this approach. The canned-motor pumps that are frequently used in association with evaporator operation at LWRs have required excessive maintenance. Replacing them with open-impeller centrifugal or axial-flow pumps, especially for transfer of viscous or gritty solutions, has cut required maintenance times.

This review of the applications of evaporators 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 required if evaporation is to be used more effectively – especially if corrosion is to be controlled. Studies are needed on the effect that antifoam agents in evaporator concentrates have on the solidification (e.g., with cement, urea-formaldehyde resins, etc.) of these concentrates. More tests, with feed that closely resembles the actual feed, carried out in a manner (e.g., semicontinuous) and under conditions (temperature, pressure, flow rate, etc.) that simulate as closely as possible those of the large-scale operation being modeled, would be helpful. Evaporators to be used on radioactive liquids should be tested before use on actual waste streams. This is probably the only reliable method of demonstrating that the desired DF values can be achieved over the extremes of conditions expected. Stable isotopes and tracer levels of radioactivity can be used in these tests. Predicted improved operating performance should then be confirmed in the plant on actual waste streams.

2. BACKGROUND

The purposes of this study were to collect, collate, and report information on the performance of evaporators for radioactive liquids in light-water-cooled nuclear reactor (LWR) power plants. Information collected includes type of evaporator used, kind of liquid evaporated, and efficiency with which radionuclides are removed from the stream treated, as well as a comparison of design specifications and operating performance. The results of this study provide operating data to assist the Nuclear Regulatory Commission (NRC) and the nuclear power industry in their evaluation of the efficiency of evaporators used in nuclear power plants. In a broader sense, the results are needed to evaluate the role of evaporation in lowering the radioactivity in the liquids discharged from any nuclear installation.

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)[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 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. Surveys similar to this one on evaporation are given in ref. 4 on the use of filtration and in refs. 5 and 6 on the use of ion exchange in LWR plants. This survey constitutes a revision of the survey[7] made by Oak Ridge National Laboratory (ORNL) in 1973 on the uses of evaporation in nuclear installations.

As a part of this study, a number of installations were contacted to obtain performance data on evaporators used to treat liquids 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), 6 evaporator 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 nonradioactive and radioactive materials comparable to those in LWR plants. Fundamentals of evaporation were considered to facilitate the technical assessment of the data gathered in the study.

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

3. LIQUID STREAMS EVAPORATED AT LWR PLANTS AND EVAPORATOR REQUIREMENTS

The liquid streams that are evaporated at PWRs are somewhat different from those at BWRs with respect to their chemistry. However, in both types of LWRs, the basic corrosivity and performance (e.g., heat transfer, feed rates, fouling, and scaling) requirements placed on evaporators are roughly the same as for evaporators used in other industries. The constraints imposed by the radioactivity content of the liquids treated are unique and necessitate design considerations that provide for shielding and remote operation. In this section the LWR streams that may be evaporated are described, and the evaporator requirements are touched on briefly.

3.1 Pressurized Water Reactors (PWRs)

In the primary system of a PWR, evaporators are frequently used to concentrate boric acid in the boron recovery part of the chemical and volume control subsystem. These evaporators, therefore, are not usually considered as waste evaporators. Waste evaporators are often used in the liquid radioactive waste (radwaste) subsystem[8] to reduce the volumes of the miscellaneous and/or chemical wastes that are normally solidified for offsite shipment. Some of the newer PWR plants that do not have once-through steam generators (OTSGs) can use evaporation as an alternate to ion exchange for treating steam-generator blowdown wastes from the secondary system. Each of the streams in which evaporators are used has distinguishing characteristics that determine the type and size of the evaporator needed as well as the materials of construction most likely to give long trouble-free service.

The borated feed to the boron recovery evaporator (i.e., reactor coolant) usually has boron concentrations in the 30- to 2000-ppm range at pH of 4.5 to 10. The ionic sodium, lithium, chloride, and fluoride concentrations are normally <0.005, <0.01 to 2, 0 to 0.15, and 0 to 0.1 ppm respectively. Hydrazine and ammonia may also be present in amounts of ≤ 20 and 0.5 ppm respectively. Total suspended solids are

<0.5 ppm on the average, with 1 to 2 ppm being the allowable maximum. Other constituents that have specified maximum concentrations are chloride and fluoride, with respective values of 0.3 and 0.1 ppm. The maximum boron concentration reported in this stream is $\sim$4400 ppm. The gross β-γ radioactivity of the feed to the evaporator is expected to be $\sim 10^{-3}$ to 10^{-2} μCi/ml. The evaporators used to concentrate such coolant water for recycle in some of the new large PWRs are designed to handle 15 to 30 gpm while producing concentrate (thick liquor) containing at least 6 to 12% boric acid by weight. For boron recycle evaporators, the 300-series stainless steels have apparently been satisfactory materials of construction. The evaporator condensate may also be recycled within the plant after polishing by ion exchange.

The chemical waste stream may have its own evaporator, or it can be processed through the miscellaneous waste evaporator, as shown in Fig. 1. The chemical waste is made up largely of spent resin regenerant solutions but also contains waste solutions from laboratory drains, some chemical cleaning wastes, and decontamination agents. Chemical waste typically has a pH of 4.5 to 11 and contains 20 to 1100 ppm boron (as tetraborate) or 3500 to 11,000 ppm boron (as boric acid), depending upon the pH. The amounts of sodium and ammonium sulfate regenerants can vary widely, from 500 to 10,000 ppm and from 600 to 5000 ppm respectively, while the ionic calcium and chloride concentrations may be approximately 450 and 120 ppm respectively. In addition to traces of resin fines, other suspended solids in the waste can range from 1 to 1000 ppm. Citric acid, potassium permanganate, ethylene diamine tetraacetic acid (EDTA), etc., from cleaning and decontamination operations may also be present in trace to 1000-ppm concentrations each. The β-γ radioactivity level of this stream is expected to be 10^{-3} to 10^{-1} μCi/ml.

The miscellaneous waste is collected from floor drains, the station sampling system, outdoor controlled areas, aerated system equipment drains, primary system ion exchangers and filters, the fuel-handling system, and reactor-coolant auxiliary systems; in some cases, the steam-generator blowdown system wastes are also included (see Fig. 1). The makeup of the miscellaneous waste stream is highly variable, and the

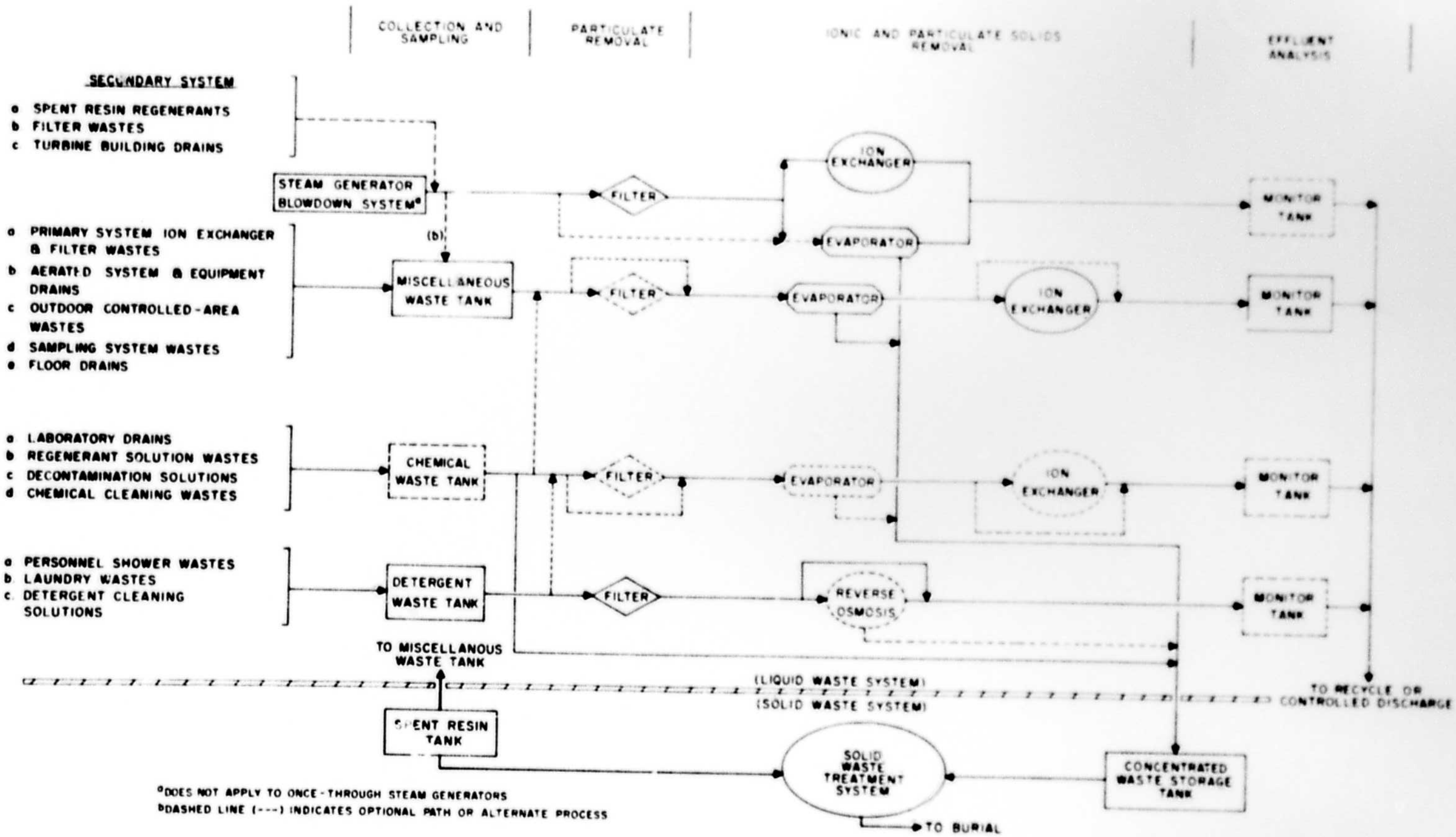


Fig. 1. Flow diagram of a basic liquid radioactive waste processing system for a PWR. (Adapted from a similar drawing in American National Standard N199-1976/ANS-55.2).

usual amounts of the numerous substances most often occurring in it are best described by the tabulation presented in Table 2. The pH of this waste stream is usually in the range 3 to 8.4. The miscellaneous waste is usually pumped to the waste evaporator at close to ambient temperature. In older PWRs, these evaporators had capacities in the 2- to 15-gpm range; in newer PWRs, they are in the 15- to 35-gpm range. The gross β-γ radioactivity level in this stream can be as high as 1.5 μCi/ml or more. The possibility of high chloride concentrations occurring along with large changes in pH indicates that the waste evaporator should either (1) be constructed of highly corrosion-resistant materials; (2) be equipped with dependable automatic instrumentation to analyze, sample, and adjust the operating conditions; or (3) have adequate, easily accessible means for manual sampling and stream adjustment. Past experience has shown that waste evaporators in LWRs are susceptible to corrosion unless careful control of pH and/or chloride concentration is exercised.[9,10] Tube plugging, corrosion, and inadequate capacity have been the major problems with waste evaporators at PWRs.

Table 2. Substances frequently found in miscellaneous waste streams at pressurized water reactors and an estimate of their concentrations

Substance	Concentration (ppm)	Substance	Concentration (ppm)
Boron	0–10,000	Other corrosion products	<1
Sodium thiosulfate[a]	~80	Calcium, magnesium	0.2–20
Morpholine[a]	1–30	Sodium, potassium	1–20
Cyclohexylamine[a]	1–30	Phosphate	0.3–<40
Ammonia	trace–30	Chromate	trace–5
Hydrazine	trace–30	Chloride, fluoride	1–200
Peroxide, permanganate, EDTA, and citric, oxalic, nitric, and hydrochloric acids	traces of each possible	Antifoam[a]	~100
		Detergents, soap	1–1,000
		Oils	trace–200
Si as SiO_2	1–20	Crud, dust	~10
Fe as oxides	0.04–1	Total suspended solids	1–1,000

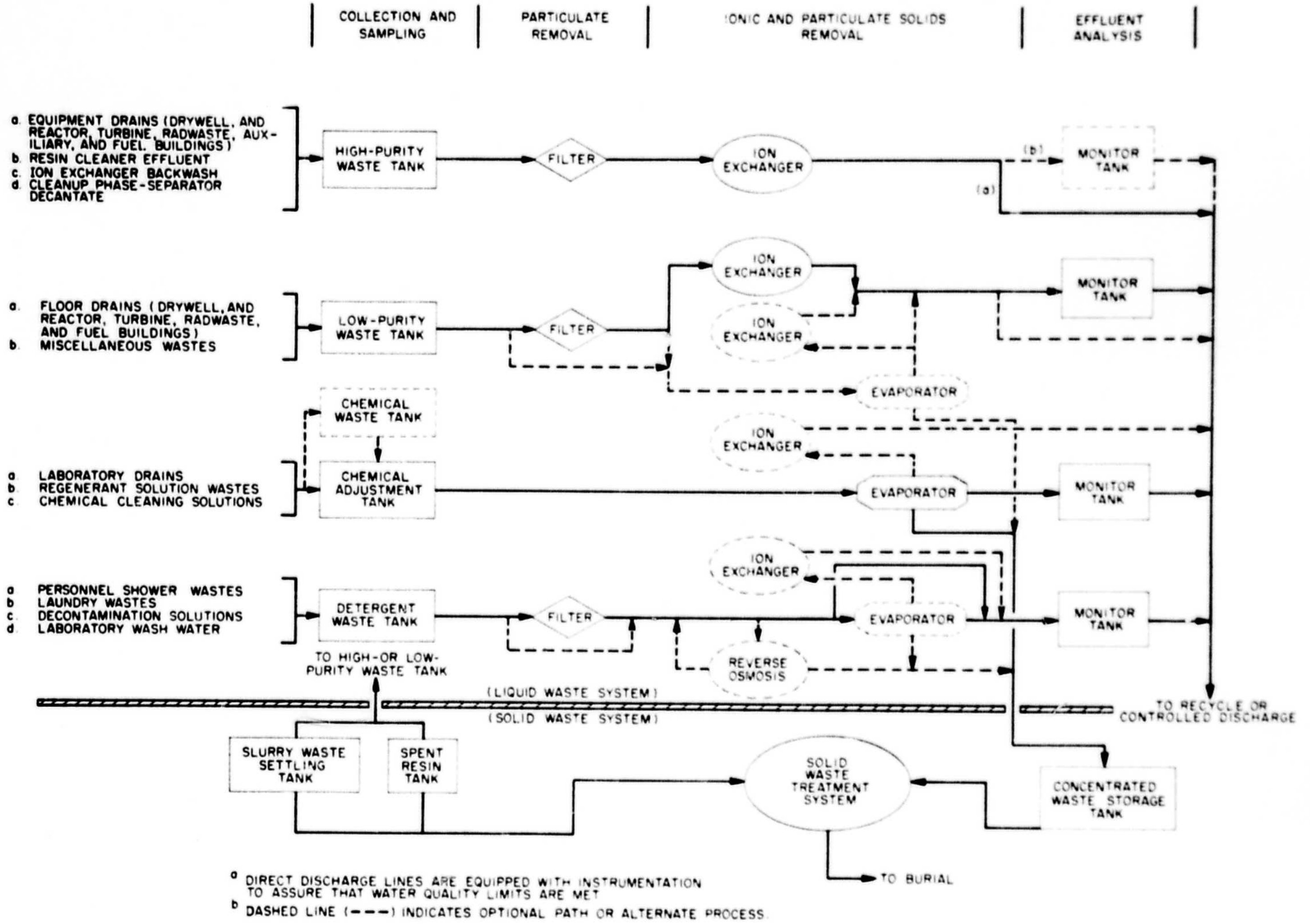
[a] Not used at all plants.

The steam-generator blowdown system waste normally has a pH of 7.5 to 9.5 and no boron if there is no primary to secondary system leakage. Ammonia, calcium carbonate, and chloride ion are present in amounts of 0.25, 0.15, and 0.15 ppm respectively, and the total suspended solids range from 1 to 5 ppm depending upon whether or not leakage occurs. If leakage does occur, the ammonia concentration also increases, and a boron concentration as high as 50 ppm or more may be found in the blowdown system waste stream. No data on radioactivity level (leakage conditions) were available for this system.

3.2 Boiling Water Reactors (BWRs)

Many BWRs do not have evaporators, since ion exchange with non-regenerable powdered resins is used exclusively for stream cleanup. Most BWRs that do have deep-bed bead-resin ion exchangers for condensate polishing do regenerate the resins. The regenerants become radioactive chemical wastes, which are usually volume-reduced by evaporation prior to solidification (as shown in Fig. 2).[11] The neutralized chemical waste has pH 6 to 9 and consists mostly of sodium sulfate at up to 20,000-ppm concentration. Also present are varying small amounts of iron, calcium, magnesium, silicon, and corrosion product compounds that may include carbonates, sulfates, chlorides, phosphates, and oxides. These wastes can also contain small amounts (1 to 1000 ppm) of decontamination agents such as citric acid, potassium permanganate, and EDTA. The gross β-γ radioactivity level of this stream may be as high as 10^{-1} μCi/ml.

In addition to the chemical wastes, the low-purity waste stream may also be evaporated at a BWR. This low-purity stream is comprised mainly of collected floor drain wastes and the liquids from resin dewatering operations. Here, too, the pH is normally in the range 6 to 9, and the average suspended solids concentration (some of which is iron oxides and silica) is approximately 20 to 500 ppm. A conductivity of 10 to 200 μmho/cm for these wastes indicates that they also contain moderate amounts of soluble compounds, namely, sodium, calcium, magnesium, and corrosion product salts such as sulfates, phosphates, carbonates,



[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).

chlorides, and fluorides. There may also be traces of organics (e.g., antifoams). The usual activity level of low-purity waste is around 10^{-3} μCi/ml of gross β-γ.

In the past, several BWR plants experienced severe stress corrosion problems with their 300-series stainless steel waste evaporators.[9,10] This has precipitated a tendency toward fabrication of current and future evaporators with such corrosion-resistant materials as Incoloy 825, Inconel 625 and/or Alloy 20. Tube plugging and inadequate sizing (capacity) have been prevalent problems at BWRs as well as at PWRs.

3.3 Detergent Wastes (PWRs and BWRs)

The detergent wastes arising from personnel showers, laundry water, and some decontamination operations are normally very low in radioactivity level (i.e., 10^{-7} to 10^{-4} μCi/ml of gross β-γ) but can have dissolved solids concentrations up to 1000 ppm. Suspended solids concentrations (e.g., lint) can also be fairly high. Under ordinary circumstances at most LWRs, these wastes are collected separately and are merely filtered prior to discharge to the environment, as indicated in Figs. 1 and 2. Many nuclear power plants have the option for solidifying detergent wastes directly, and still others have provisions for concentrating these wastes by reverse osmosis or evaporation before the solidification step. The introduction of detergents into an evaporator can cause foaming problems, which may make the use of antifoaming agents mandatory for proper evaporator operation. The effects of antifoam on the solidification processes in common use at nuclear power plants are not well defined at present.

4. GENERAL DESCRIPTION OF EVAPORATORS USED AND PROPOSED FOR USE AT LWR PLANTS

Evaporation is the process by which the volatile and nonvolatile components of a solution or slurry are separated via boiling away the volatile component. It is a unit operation that has wide application at PWR plants for concentrating boric acid solutions and at PWR and BWR plants for reducing both waste volumes and the amount of radioactivity in liquid effluents. Evaporation can be used on solutions or slurries having widely different compositions and concentrations (e.g., as described in Sect. 3); however, it is most effectively used on liquid radwastes having high concentrations of impurities.[12]

Among the important elements involved in evaporator design are heat transfer, separation of evolved vapor from residual liquid, volume reduction, prevention of fouling of the heating surface, and conservation of energy. In the design of evaporators for nuclear power plants, vapor-liquid separation is the most important factor because decontamination of the liquid is the most important objective. In this application the heating costs and volume reduction (concentrating boric acid is probably an exception) are relatively less important. Selection of construction materials is also important since corrosion can be a problem which reduces the life of an evaporator. The elements involved in evaporation are described generically in standard chemical engineering texts (e.g., refs. 13-17), handbooks (e.g., refs. 18 and 19), and encyclopedias (e.g., refs. 20-22). Some of these elements are reviewed briefly in Appendix A.

An evaporator is a device designed to transfer heat to a liquid (solution or slurry) that boils and to separate the vapor thus formed from the boiling liquid. The unit or building block in which heat transfer takes place may be called a calandria, heating element, heat exchanger, heater, or tube bundle. The unit in which vapor-liquid separation takes place may be called a body, flash chamber, or vapor head. The term body is also used to denote the minimum basic units needed to form an evaporator, that is, one heater and one flash chamber. The concentrated solution or slurry removed from the evaporator is variously called bottoms, concentrate, discharge, strong liquor, or thick liquor. Evaporators that are used or proposed for use at LWRs employ tubular heating surfaces. Tubes may be long or short, straight or bent, and may have uniform or tapered cross sections. The heat-transfer medium or fluid (usually steam at LWRs) may be inside or outside the tubes. The flash chamber and heater may be an integrated unit (integral or internal heater), or they may be separate units (separate or external heater). The heater may be horizontal or vertical. The movement of liquid past the heating surface may be induced either by gravity or the density variations brought on by boiling (natural circulation) or by mechanical means such as a pump or propeller (forced circulation). Evaporators may be operated as once-through or as circulation units. In once-through operation, the feed liquor passes through the tubes only once. In this single pass, it releases vapor and leaves the unit as thick liquor. In circulation operation, the feed mixes with liquid that has passed through the tubes one or more times, and the mixture passes through the tubes. In this mode of operation, only part of the total evaporation occurs in a single pass. Evaporator accessories include devices such as condensers, entrainment separators, feed preheaters, gas strippers, vent systems for noncondensable gases, and appropriate instrumentation. A review of evaporators used in nuclear installations through about May 1968 is given in ref. 23 and through about June 1973 in ref. 7. Some technical trade-offs in designing evaporators for LWR plants are presented in ref. 24, and some experiences with entrainment from and corrosion of radwaste evaporators are given in ref. 25.

Evaporators may be categorized in a number of ways (e.g., refs. 13-23) depending usually upon the classifier's interest. Since a measure of evaporator performance as judged by the decontamination factor achieved is the prime interest of this study, a division that seems to bring out this point has been selected. The types of evaporators that are used or proposed for use at nuclear power plants have been roughly divided into four main categories: natural circulation (NC), forced circulation (FC), spray film (SF), and submerged U-tube (SU). These types are described in the following sections.

4.1 Natural-Circulation Type

Natural-circulation evaporators with long-tube vertical (LTV) heaters may be of the type in which the liquid flows upward through the tubes (climbing or rising film) or the type in which the liquid flows downward through the tubes (falling film).

4.1.1 Rising film

Internal (Fig. 3) and external (Fig. 4) heaters can be employed with the rising-film LTV evaporator. In these units liquid enters the bottom of the tubes and flows upward (as liquid) receiving heat. Bubbles then form in the liquid as boiling begins, increasing the linear velocity. Near the top of the tubes the bubbles grow rapidly. In this zone bubbles of vapor alternating with slugs of liquid rise very quickly through the tubes and emerge at high (sometimes approaching sonic) velocities from the top.

4.1.1.1 Internal heater. A rising-film LTV evaporator with an internal heater, which consists simply of a vertical shell-and-tube heat exchanger surmounted by a flash chamber, is depicted in Fig. 3.

4.1.1.2 External heater. To permit easy access to the tubes for cleaning, maintenance, or replacement, the heater of a rising-film LTV evaporator may be at one side of the flash chamber, as shown in Fig. 4.

4.1.2 Falling film

The principal disadvantage of the rising-film LTV evaporator is poor heat-transfer performance (under some conditions) due to hydrostatic head, friction, and acceleration of the liquid by the vapor. This disadvantage can be almost completely mitigated by turning the rising-film LTV evaporator (Fig. 3) upside down, as in Fig. 5. In the falling-film (FF) LTV evaporator, liquid enters at the top, flows downward inside the tubes as a film, and exits from the bottom. Vapor evolved from the liquid flows concurrently. The chief problem with the FF evaporator is that of attaining uniform distribution of liquid to the top of all the tubes. Although the FF evaporator shown in Fig. 5

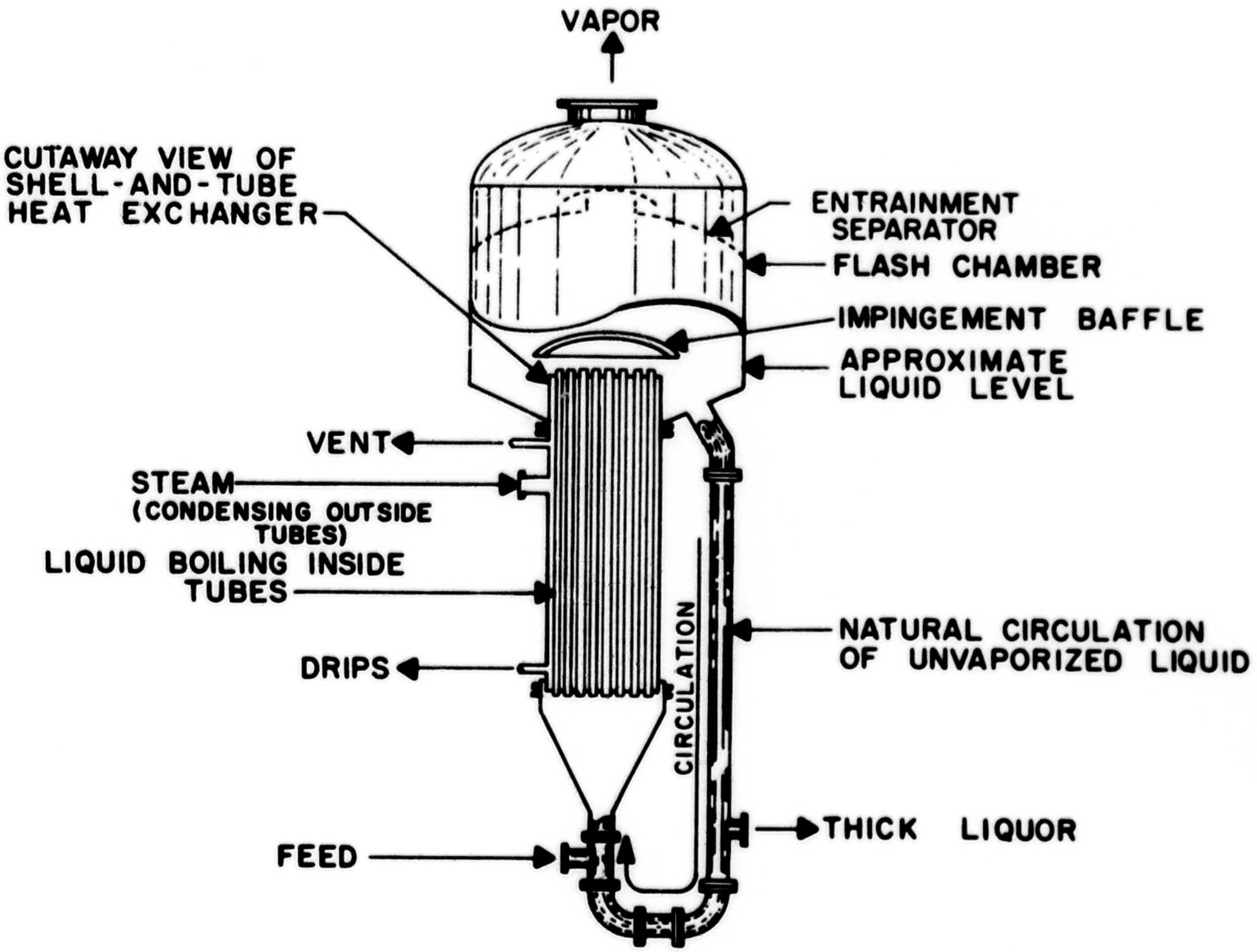


Fig. 3. Natural-circulation, rising-film, long-tube vertical evaporator with an internal heater.

ORNL DWG 72-1395R3

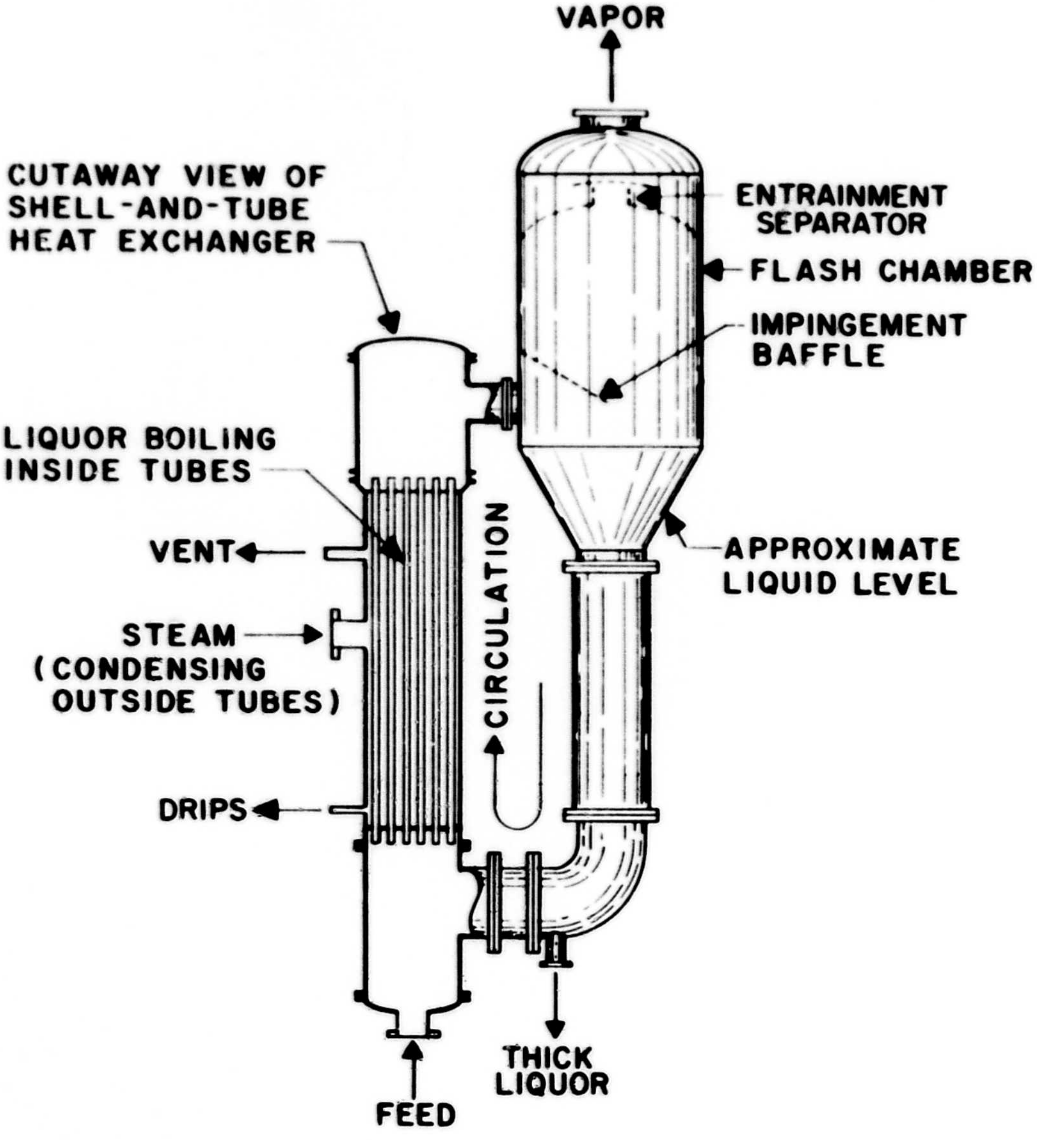


Fig. 4. Natural-circulation, rising-film, long-tube vertical evaporator with an external heater.

ORNL DWG. 73-6869R2

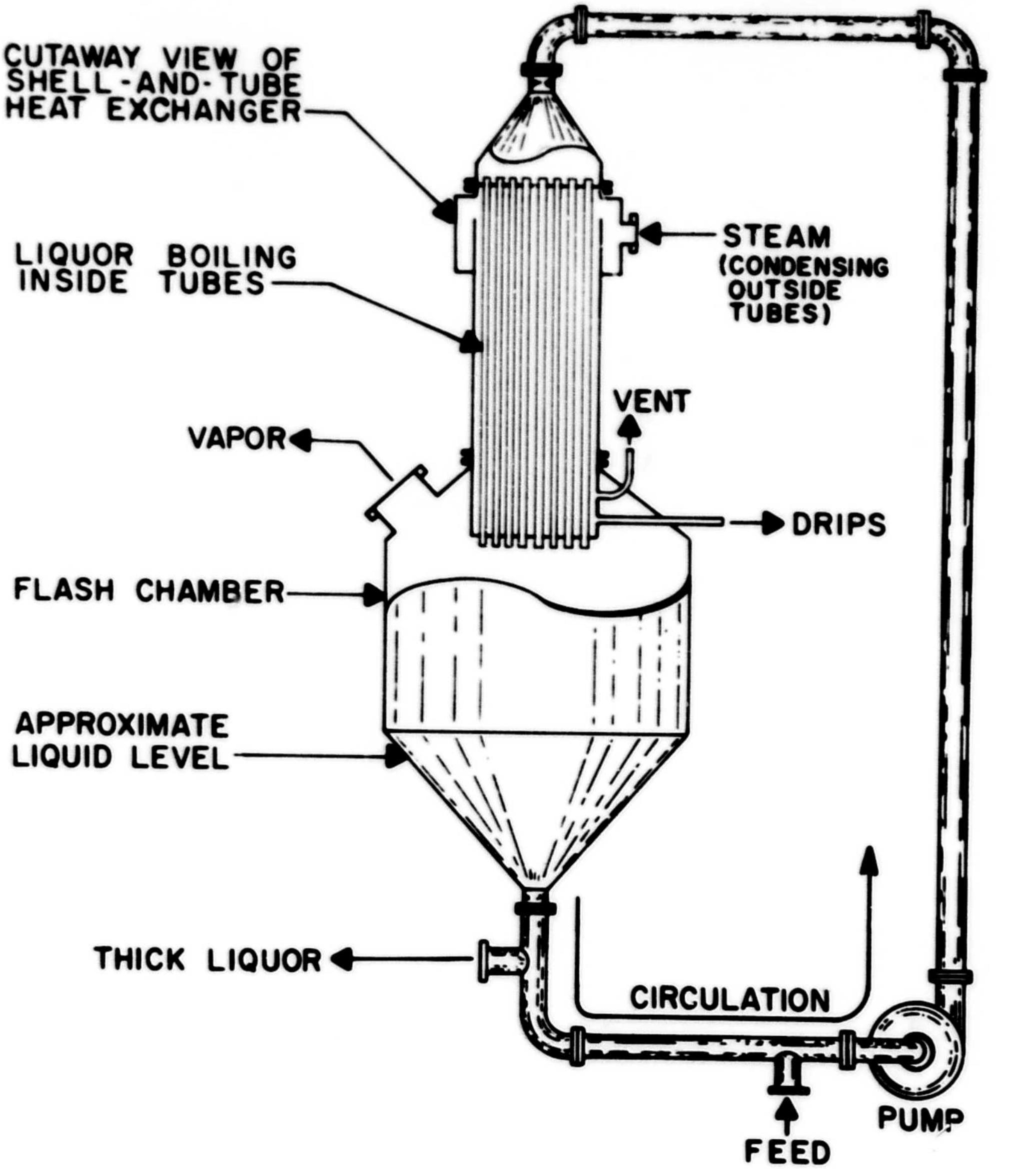


Fig. 5. Falling-film, long-tube vertical evaporator.

has a pump, it is not a forced-circulation evaporator since mechanical energy is used merely to circulate liquid to the top of the tubes and not to improve heat transfer.

4.2 Forced-Circulation Type

Evaporators in which the liquid is forced over the heating surface by a pump are especially suited for liquids that are foamy or viscous and that tend to deposit scale or crystals on the heating surface. If a crystallizing evaporator is employed, forced circulation is essential to keep the crystals in motion to prevent blockage of the tubes and to control crystal growth. If a pump were inserted between the heater and the feed port of the LTV evaporator in Fig. 3, the resultant unit would represent an FC evaporator with an internal heater. However, FC evaporators with external heaters are considered better suited to use in LWR plants because the components (flash chamber, heater, pump, condenser, etc.) may be separated to the maximum extent possible. This makes shielding easier and maintenance quicker so that the radiation exposure may be kept at a minimum.

4.2.1 External heater

The heater may be either horizontal (usually two pass) or vertical (usually single pass). Single pass means that the fluid being heated flows through the heater in only one direction; two pass means that the fluid flows through part of the tubes in one direction and through the remainder of the tubes in the opposite direction.

4.2.1.1 Horizontal. Figure 6 shows a forced-circulation evaporator with an external, horizontal, two-pass heater. The heater is placed far enough below the liquid level to ensure that there is no boiling in the tubes (submerged tubes).

4.2.1.2 Vertical. Figure 7 shows a forced-circulation evaporator with an external, vertical, single-pass heater. The FC evaporator shown in Fig. 6 has the heater placed far enough below the liquid level in the flash chamber to suppress boiling in the tubes. A restriction device

ORNL DWG. 73-5932R2

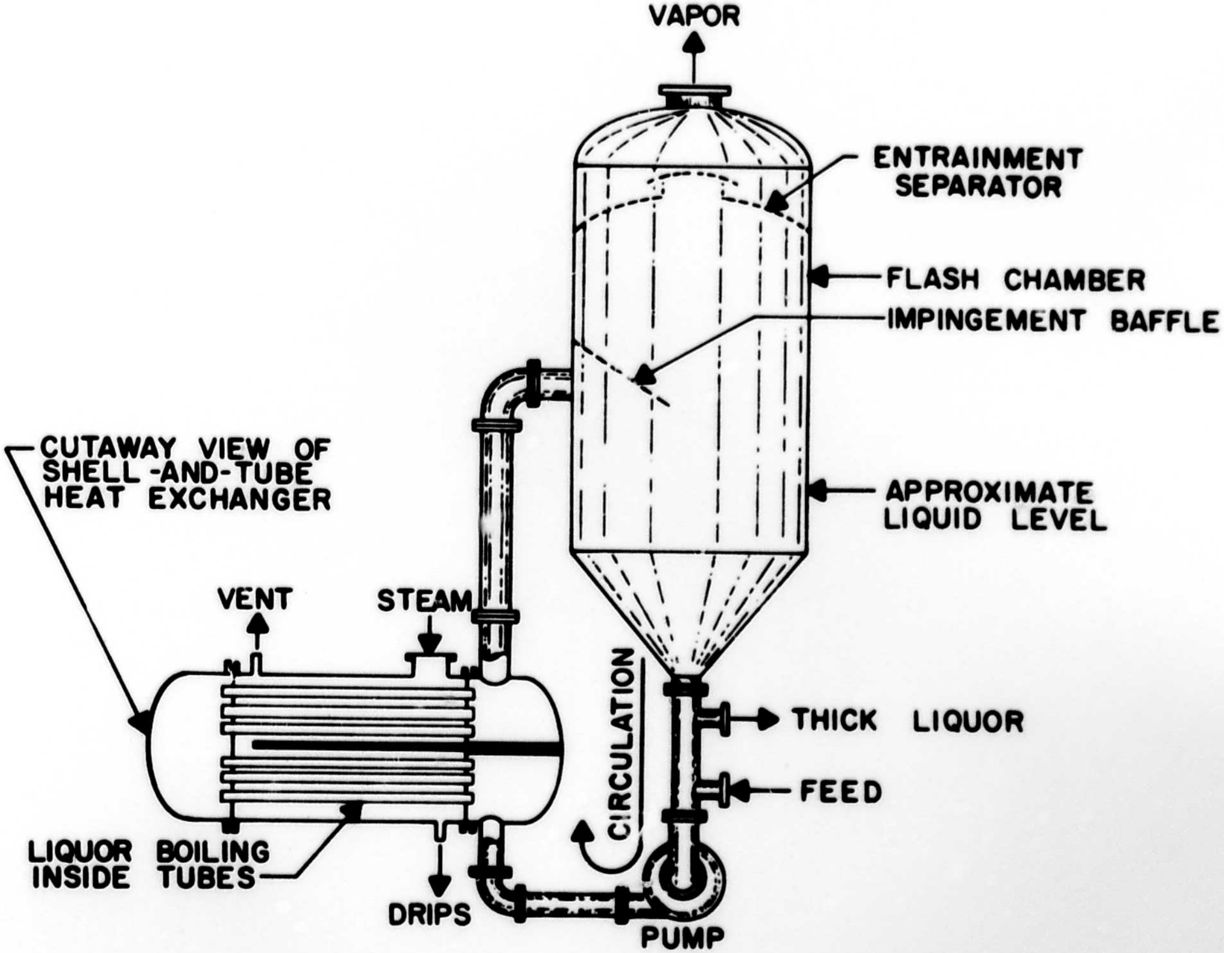


Fig. 6. Forced-circulation evaporator with an external, horizontal, submerged-tube, two-pass heater.

ORNL DWG 78-5011

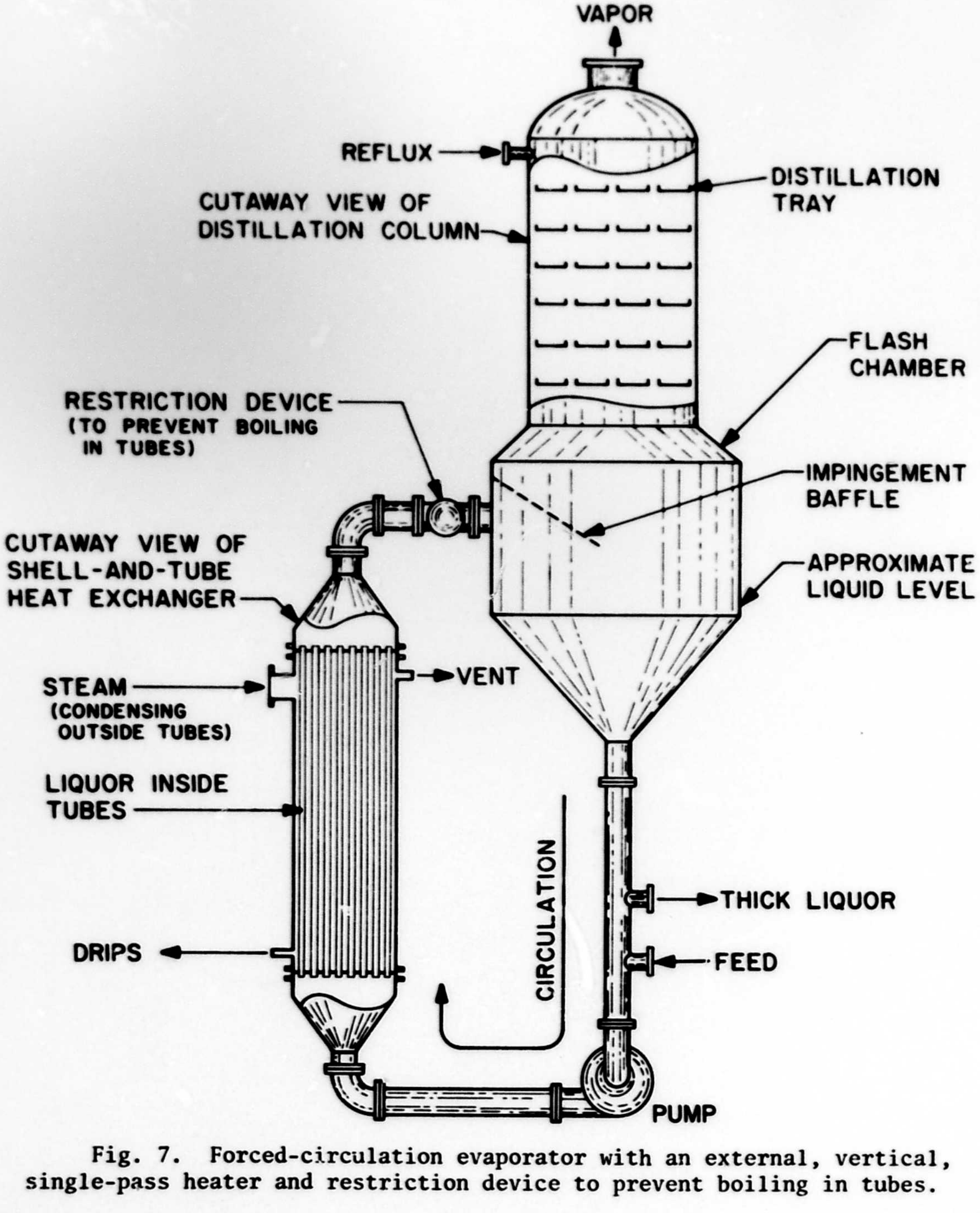


Fig. 7. Forced-circulation evaporator with an external, vertical, single-pass heater and restriction device to prevent boiling in tubes.

(e.g., orifice or valve) or piping pressure drop in the return line to the flash chamber can also prevent boiling in the tubes. A restriction device is illustrated in Fig. 7. This unit also illustrates a tray column above the flash chamber. The purpose of this column is to scrub entrained liquid droplets from the vapor using some of the condensed vapor as scrub liquid.

4.2.2 Evaporator/crystallizer

Evaporation techniques for the crystallization of salts have been used for centuries. Forced-circulation evaporators are well suited to concentrating salting liquors, and so function as evaporating crystallizers (or crystallizing evaporators).[26-36] In this study, such a unit is referred to as an evaporator/crystallizer since whether it is an evaporator or a crystallizer is largely a question of the shape of the solubility curve of the material on which it operates. An evaporator/crystallizer is illustrated in Fig. 8.

4.2.3 Wiped film

The wiped-film evaporator[37-40] is considered as a forced-circulation type since it uses mechanical energy to improve heat transfer. These machines are also called agitated-, scraped-, thin-, and turbulent-film evaporators. The heating surface consists of a single, large-diameter, cylindrical or tapered tube. The liquid being concentrated is spread out into a thin, highly turbulent film by the blades of the rotor. Wiped-film evaporators are usually operated in a once-through mode. They are available in either horizontal (Fig. 9) or vertical models.

4.3 Spray-Film Type

The spray-film evaporator (Fig. 10) might also be categorized as a forced-circulation type inasmuch as it uses mechanical energy to improve heat transfer. Energy is required to force the liquid being evaporated through spray nozzles to atomize it. The small droplets formed impinge upon the heat-transfer surface and spread over it in a thin film. The

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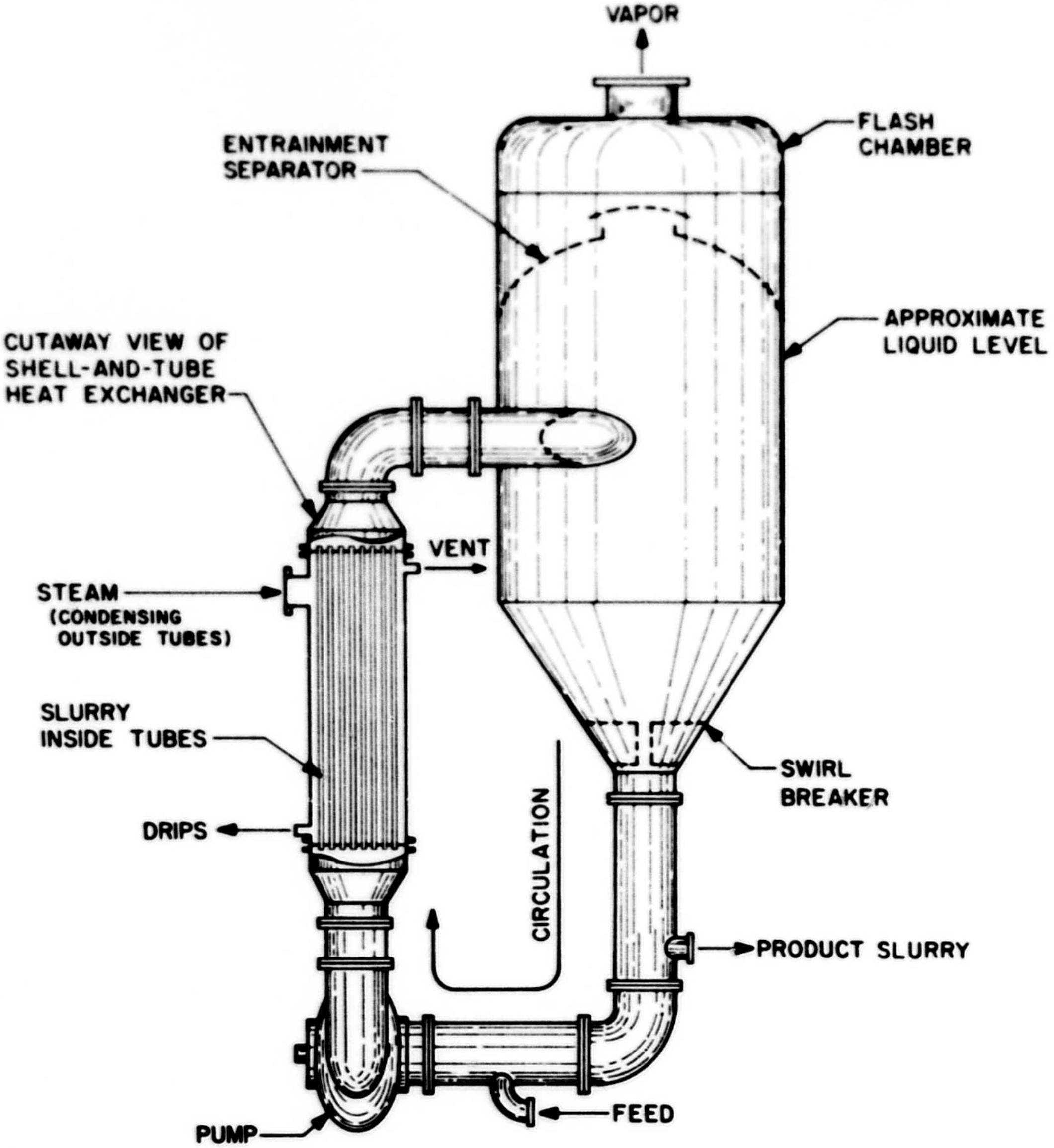

Fig. 8. Evaporator/crystallizer.

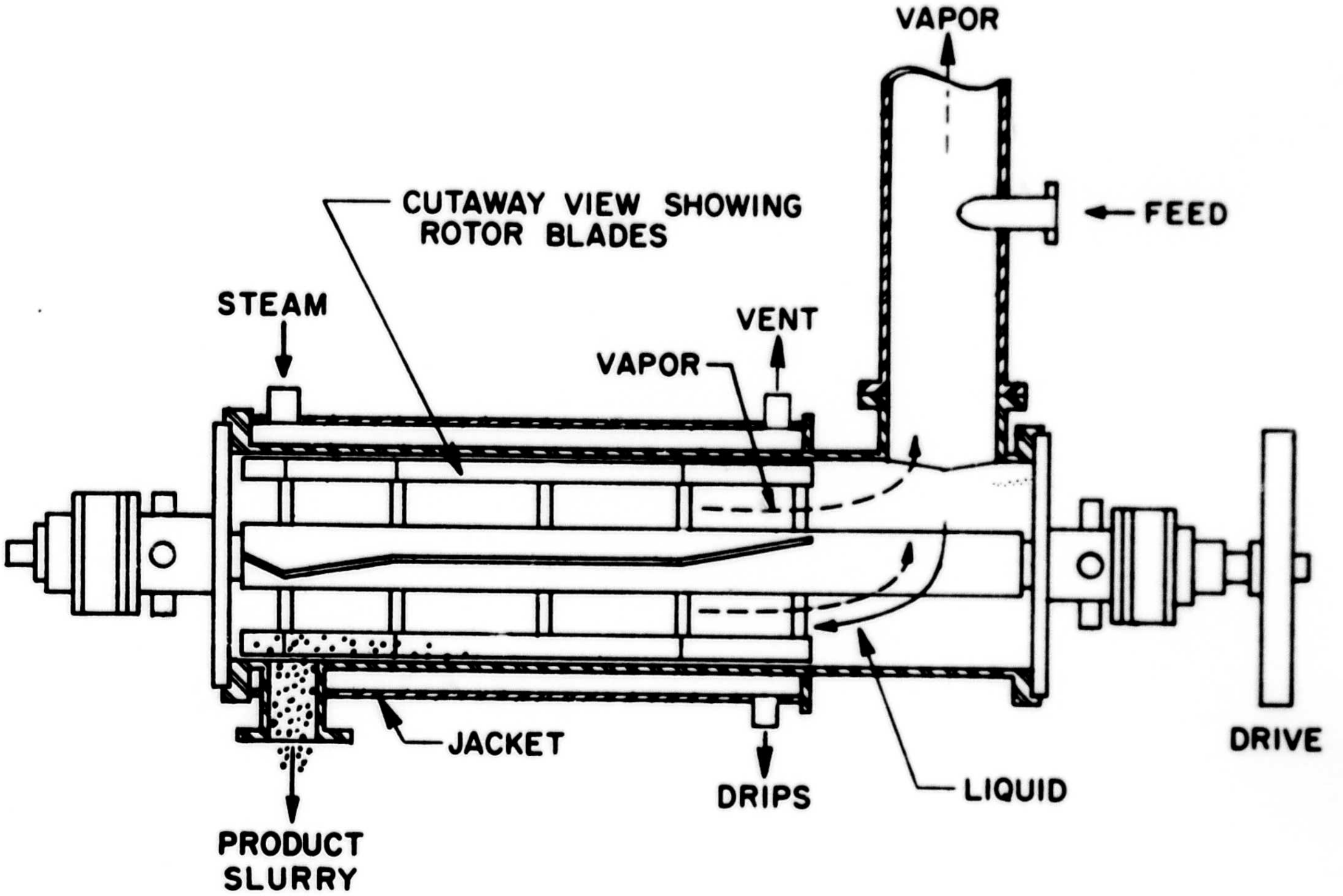

Fig. 9. Wiped-film evaporator.

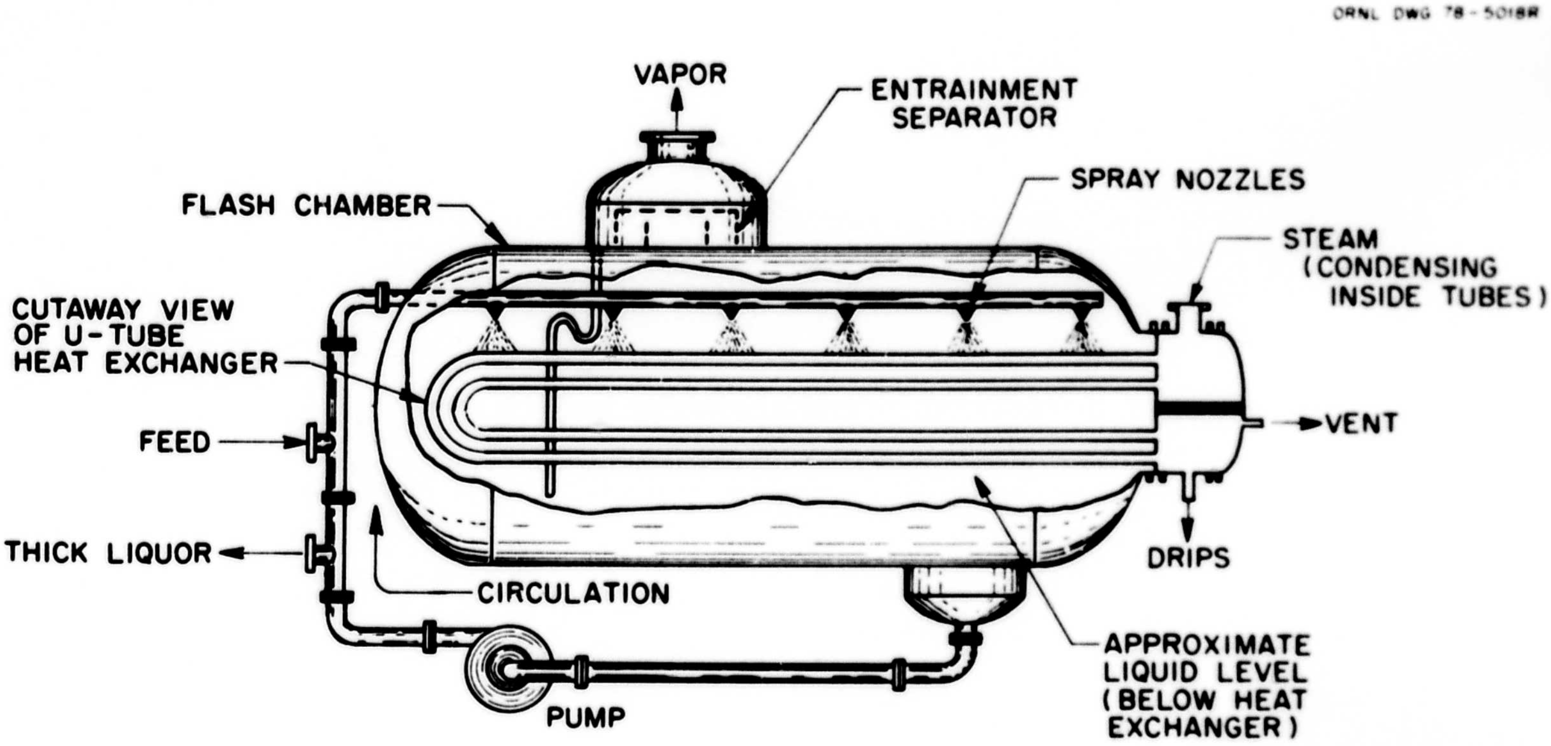

Fig. 10. Spray-film evaporator with horizontal U-tube heater.

pool of liquid being circulated is below the heater (Fig. 10). This is the first evaporator considered in this study in which the heat-transfer medium is confined within the tubes. In all the previously mentioned types, the liquid being evaporated was inside the tubes.

4.4 Submerged U-Tube Type

Another type of evaporator used in LWR plants in which the heat-transfer medium is inside the tubes is the submerged U-tube (Fig. 11). The liquid being concentrated completely covers the horizontal, U-bend heating tubes, circulation being obtained by natural convection and boiling of the liquid (i.e., it is a natural-circulation unit). The pump shown in Fig. 11 is for circulation and not for enhancing heat transfer. Operation under vacuum is not uncommon with evaporators of this type, in which case, it is sometimes feasible to use hot water as the heat-transfer medium instead of steam.

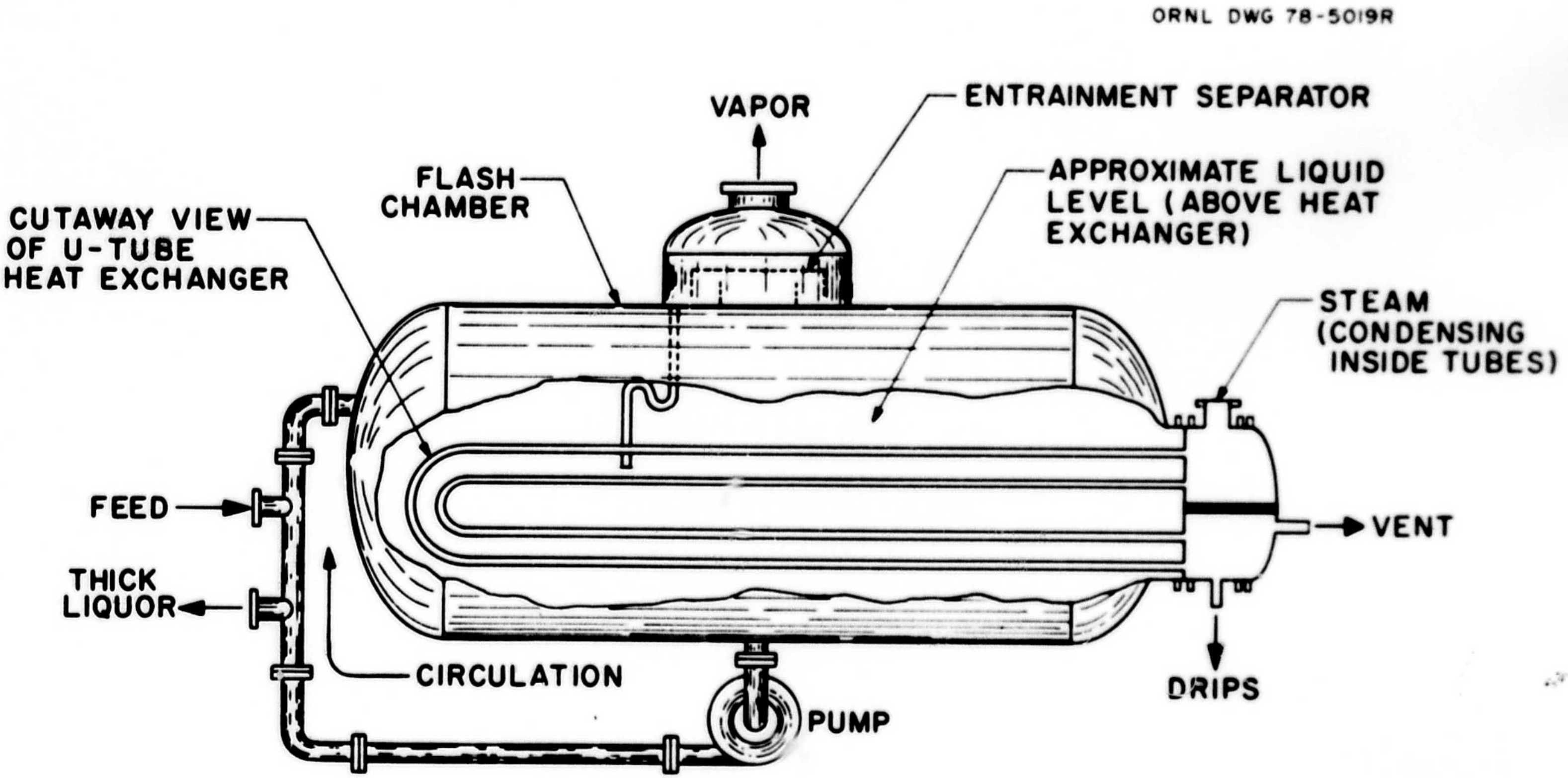

Fig. 11. Submerged U-tube evaporator.

5. SOME FACTORS INFLUENCING EVAPORATOR SELECTION AND PERFORMANCE

The principal engineering considerations involved in the design of an evaporator for radioactive liquids are heat transfer and vapor-liquid separation. Reliable and maintenance-free operation are important factors that must also be taken into account. The selection of corrosion-resistant materials of construction and a design that minimizes the loss of heat-transfer surface (due to deposition of films or solids of low thermal conductivity) are vital to avoiding loss of capacity as well as operational and maintenance problems. Other factors influencing the design include the amount by which the feed is to be reduced in volume and total operating costs. Some factors that have an effect on evaporator selection and performance[41-51] are discussed briefly in the following sections. A few others that influence evaporator selection and performance are presented in Appendix A.

5.1 Design Considerations

Among the important factors that should be known or determined before the most efficacious evaporator can be chosen are:

a. Physicochemical properties. The physical and chemical properties (e.g., density, viscosity, and surface tension) of the liquid in the evaporator are needed as a function of temperature over the concentration range of the feed (thin liquor) and the concentrated liquid (thick liquor).

b. Mode of operation. Method of operation can affect results and influence the choice of evaporator type. A knowledge of the expected mode of operation (batch, continuous, or semicontinuous, as described in Sect. 10 and Appendix A) is necessary.

c. Capacity. The minimum, maximum, and average capacity (mass of solvent to be evaporated per unit of time) at which the evaporator will be expected to operate is required information.

d. Heat-transfer medium. The temperature, pressure, and quantity of heat-transfer medium (usually steam) available must be known.

e. Salting, scaling, and fouling. The possibility of salting, scaling, and fouling (as defined in Sect. 10) must be determined and their effects evaluated.

f. Corrosion. Data on corrosion under the anticipated conditions of operation must be determined.

g. Cleaning, inspection, and maintenance. Consideration must be given to ease of cleaning (chemical and/or mechanical), access for inspection and maintenance (remote and/or direct), and the time required for these operations.

h. Untoward conditions. Possible explosion conditions due to unstable organics (e.g., amines) or combustible gases (e.g., hydrogen) must be covered.

i. Available space. Attention must be given to headroom and floor-space requirements. Segregation and shielding of components must be considered.

j. Controls, instrumentation, and sampling. Adequate controls, instruments, and sampling points must be incorporated for efficient evaporator performance.

k. Economics. Cost of the evaporator and its operation must be taken into account.

5.2 Some Merits and Demerits

The merits and demerits of various evaporators are summarized in refs. 18 and 19. A qualitative evaluation of evaporator types now in use or proposed for future use in LWR nuclear power plants is given in Table 3.

Table 3. Some merits and demerits of the evaporator types[a] used in light-water reactor power plants

	Evaporator type		
	Natural circulation[b]	Forced circulation[c]	Submerged U-tube[d]
Advantages	1. Low cost 2. Large heating surface in one body 3. Low hold-up 4. Small floor space 5. Good heat-transfer coefficients at reasonable temperature differences (rising film) 6. Good heat-transfer coefficients at all temperature differences (falling film)	1. High heat-transfer coefficients 2. Positive circulation 3. Relative freedom from salting, scaling, and fouling	1. Very low headroom 2. Large vapor-liquid disengaging area 3. Good heat-transfer coefficients 4. Easy semiautomatic descaling
Disadvantages	1. High headroom 2. Generally unsuitable for salting and severely scaling liquids 3. Poor heat-transfer coefficients of rising-film version at low temperature differences 4. Recirculation usually required for falling-film version	1. High cost 2. Power required for circulating pump 3. Relatively high hold-up or residence time	1. Unsuitable for salting liquids 2. High cost 3. Relatively high hold-up or residence time
Best applications	1. Clear liquids 2. Foaming liquids 3. Corrosive solutions 4. Large evaporation loads 5. High temperature differences–rising film, low temperature differences–falling film 6. Low-temperature operation–falling film	1. Crystalline product 2. Corrosive solutions 3. Viscous solutions	1. Limited headroom 2. Small capacity 3. Severely scaling liquids
Frequent difficulties	1. Sensitivity of rising-film units to changes in operating conditions 2. Poor feed distribution to falling-film units	1. Plugging of tube inlets by salt deposits detached from walls of equipment 2. Poor circulation due to higher than expected head losses 3. Salting due to boiling in tubes 4. Corrosion–erosion	1. Slow response to changes in control settings 2. Poor level control in vacuum units

[a] Taken from R. H. Perry and C. H. Chilton (eds.), *Chemical Engineers' Handbook*, 5th ed., Sect. 11, "Heat-Transfer Equipment", pp. 11–27 through 11–38, McGraw-Hill, New York (1973), with slight modification.

[b] As described in Sect. 4.1.

[c] As described in Sect. 4.2.1.

[d] As described in Sect. 4.4.

6. EXPERIENCE IN THE APPLICATION OF EVAPORATORS AT LWR PLANTS

The responses to the ORNL survey from 28 of the 62 reactors (excluding Shippingport) that were operating at the end of 1976 provided operating data on streams evaporated and design descriptions of the evaporators used in each case. These data, plus information gathered from NSSS vendors, architect-engineers, and suppliers of evaporation equipment, were compiled and tabulated. Selected design specifications for evaporators installed in these operating plants are presented separately for PWRs and BWRs in Tables 4 and 5 respectively. Similar data for plants now under construction are given in Tables B-1 and -2 in Appendix B. Some reported performance data for both types of plants are summarized in Table 6. The importance of decontamination factor (DF) as a measure of evaporator efficiency warrants special treatment, and it is covered as a separate subject in Sect. 7.

Since PWRs and BWRs differ in several respects, the application and performance of evaporators in the two types of reactors will be discussed separately. The PWRs use soluble boron in core reactivity control whereas BWRs do not. Therefore, many PWRs use evaporation for concentrating borated coolant water in their boron recycle systems, while BWRs have no analogous need. However, the radioactive miscellaneous and chemical wastes from a PWR correspond roughly to the low-purity and chemical wastes from a deep-bed BWR plant (i.e., condensate polishing is done with regenerable bead resins). Both these types of plants frequently use evaporators to reduce the volume of these wastes prior to solidification for offsite shipment (see Figs. 1 and 2 in Sect. 3).

6.1 Evaporator Applications in PWRs

All PWR plants do not apply evaporators to the same streams, nor do they use them in exactly the same way when they do evaporate the same streams. Most plants have separate evaporators for boron recycle and radwaste treatment, but several plants have them interconnected to

Table 4. Selected design specifications for evaporators installed in operating (December 31, 1976) pressurized water reactors[a]

Installation [Capacity]	Number of evaporators	Evaporator type		Materials of construction[d]	Design rating		Entrainment separator	Streams treated	Designer and/or manufacturer	Notes
		Category[b]	Heater[c]		Capacity (gpm)	Pressure (psia)				
Arkansas 1 [2568 MW(t)]	0									Eventually will share two HPD evaporator/crystallizer systems with Unit 2
Beaver Valley 1 (*) [2660 MW(t)]	3	(2 units)						Boric acid		
		FC	E,H,L	304L SS	6	30	Distillation trays	Miscellaneous, chemical, and secondary system wastes	Stone & Webster	
Calvert Cliffs 1 & 2 [2570 MW(t)] ea.		SU	I,H,S	SS	20	5	Wire mesh, plates, and trays	Boric acid	(AMF)-Riley Beaird	Single-skid mounted, contents recirculated
		SU	I,H,S	SS	20	5	Wire mesh, plates, and trays	Miscellaneous, chemical, and secondary system wastes	(AMF)-Riley Beaird	Single-skid mounted, contents recirculated
Connecticut Yankee [1825 MW(t)]	3	FC (2 units)	E,V,L	SS	20			Boric acid		Can be operated as a double-effect evaporator
		FC	E,V,L		20	30		Miscellaneous, chemical, detergent, and secondary system wastes		
Cook 1 (*) [3250 MW(t)]	3	SU (2 units)	I,H,L	SS	30	18	Wire mesh and tray	Boric acid	Westinghouse	Single-skid mounted, recirculation pump
		SU	I,H,L	316 SS	2	18	Wire mesh and packed tower	Miscellaneous, chemical, detergent, and secondary system wastes	Westinghouse	Single-skid mounted, recirculation pump
Crystal River 3 (*) [2452 MW(t)]	2	SU	I,H,S	304/316 SS	20	3–5	Wire mesh, plates, and trays	Boric Acid	(AMF)-Riley Beaird	Single-skid mounted, contents recirculated
		SU	I,H,S	304/316 SS	20	3–5	Wire mesh, plates, and trays	Miscellaneous, chemical, and secondary system wastes	(AMF)-Riley Beaird	Single-skid mounted, contents recirculated
Ft. Calhoun (*) [1420 MW(t)]	1	SF	I,H,L	304 SS/Inconel	17	17	Wire mesh	Miscellaneous, chemical, detergent and secondary system wastes	Aqua-Chem	Original SS tube bundles replaced with Inconel; recirculation pump
Ginna [1520 MW(t)]	2	SU	I,H,S	SS	12.5	6	Wire mesh and perforated plate	Boric acid and reactor makeup quality wastes	(AMF)-Riley Beaird	Contents recirculated
		SU	I,H,S	SS	12.5	4	Wire mesh, perforated plate, and sieve tray	Miscellaneous, chemical, and secondary system wastes	(AMF)-Riley Beaird	Contents recirculated
Indian Point 2 [2758 MW(t)]	3	(2 units)			12			Boric acid and reactor makeup quality wastes		
					2			Miscellaneous, chemical, and secondary system wastes		

Table 4 (continued)

Installation [Capacity]	Number of evaporators	Evaporator type		Materials of construction[d]	Design rating		Entrainment separator	Streams treated	Designer and/or manufacturer	Notes
		Category[b]	Heater[c]		Capacity (gpm)	Pressure (psia)				
Kewaunee (*) [1650 MW(t)]	2			SS			Wire mesh	Boric acid		
		SU	L.H.L	SS	2	18		Miscellaneous, chemical and secondary system wastes	Westinghouse	Used solely for operator training
Maine Yankee (*) [2440 MW(t)]	2	FC	E.V.L	304/316 SS	25	30	Moisture separator	Boric Acid	Stone & Webster	Entire system heat traced
		FC	E.V.L	316L SS	6	30	Swirl-vane separator	Miscellaneous, chemical and secondary system wastes	Stone & Webster	
Millstone 2 [2560 MW(t)]	2	SU	L.H.S	SS	25		Wire mesh, perforated plate, and sieve tray	Boric acid and reactor makeup quality wastes	(AMF)-Riley Beard	Single-skid mounted, contents recirculated
		SU	L.H.S	SS	15		Same as above	Miscellaneous, chemical and secondary system wastes	(AMF)-Riley Beard	Single-skid mounted, contents recirculated
Oconee 1, 2 & 3 (*) [2568 MW(t)] ea.	3	SF	L.H.L	SS	7.5	17–20	Wire mesh	Boric acid and reactor makeup quality wastes	Aqua-Chem	Recirculation pump, evaporators are cross connected
		SF	L.H.L	SS	7.5	17–20		Miscellaneous, chemical and secondary system wastes	Aqua-Chem	Recirculation pump
		SU	L.H.L	SS	15	18	Wire mesh	Miscellaneous, chemical and secondary system wastes	Westinghouse	Recirculation pump
Palisades (*) [2212 MW(t)]	2	SU	L.H.S	316 SS	20	5	Wire mesh	Boric acid and reactor makeup quality wastes	(AMF)-Riley Beard	Single-skid mounted, contents recirculated
		SU	L.H.S	316 SS	20	5	Wire mesh	Miscellaneous, chemical and secondary system wastes	(AMF)-Riley Beard	Single-skid mounted, contents recirculated
Point Beach 1 & 2 [1518 MW(t)] ea.	4	SU (2 units)	L.H.S	SS	12.5	6–7	Wire mesh and perforated plate	Boric acid and reactor makeup quality wastes	(AMF)-Riley Beard	Contents recirculated
		SU	L.H.S	SS	2	3	Wire mesh, perforated plate, and sieve tray	Miscellaneous, chemical and secondary system wastes	(AMF)-Riley Beard	Contents recirculated, uncertain whether this unit is still in service
		FC	E.V.L	Incoloy 825	35	30	Distillation trays	Miscellaneous, chemical, laundry and secondary system wastes	Stone & Webster	
Prairie Island 1 & 2 [1650 MW(t)] ea.	4	SU (2 units)	L.H.L	SS	15	18	Wire mesh and packed tower	Boric acid and reactor makeup quality wastes	Westinghouse	Recirculation pump
		SU	L.H.L	SS	2	18	Wire mesh and packed tower	Miscellaneous, chemical and secondary system wastes	Westinghouse	Recirculation pump
		SF	L.H.L	SS	5	17–20	Wire mesh	Miscellaneous, chemical and secondary system wastes	Aqua-Chem	Recirculation pump

Table 4 (continued)

Installation [Capacity]	Number of evaporators	Evaporator type		Materials of construction[d]	Design rating		Entrainment separator	Streams treated	Designer and/or manufacturer	Notes
		Category[b]	Heater[c]		Capacity (gpm)	Pressure (psia)				
Robinson 2 [2200 MW(t)]	3	SU (2 units)	I,H,S	SS	12.5	6–7	Wire mesh, perforated plate, and sieve tray	Boric acid	(AMF)-Riley Beaird	Contents recirculated
		SU	I,H,S	SS	2	4	Wire mesh, perforated plate, and sieve tray	Miscellaneous, chemical and secondary system wastes	(AMF)-Riley Beaird	Contents recirculated
San Onofre 1 (*) [1347 MW(t)]	0									
St. Lucie 1 (*) [2570 MW(t)]	3	NC (2 units)	I,V,L	SS	20	20	Wire mesh and trays	Boric acid	Aqua-Chem	Single-skid mounted
								None		Not used
Surry 1 & 2 [2441 MW(t)] ea.	3	FC (2 units)	E,V,L	316L		30	Distillation trays	Boric acid	Stone & Webster	
		FC	E,H,L	SS/Incoloy 825	25	30	Distillation trays	Miscellaneous, chemical and secondary system wastes	Stone & Webster	Replacement for original 6 gpm unit
Three Mile Island 1 (*) [2535 MW(t)]	2	SU	I,H,S	SS	12.5	5–7.5	Wire mesh	Boric acid	(AMF)-Riley Beaird	Contents recirculated
		SU	I,H,S	SS	12.5	5–7.5	Wire mesh	Miscellaneous, chemical and secondary system wastes	(AMF)-Riley Beaird	Contents recirculated, evaporators are cross-connected
Turkey Point 3 & 4 (*) [2200 MW(t)] ea.	4	NC (2 units)	I,V,L	SS	5	20	Wire mesh	Boric acid	Aqua-Chem	Single-skid mounted
		SU (2 units)	I,H,L	SS	15	20	Wire mesh	Miscellaneous, chemical, detergent, and secondary system wastes	Westinghouse	Single-skid mounted, recirculation pump
Yankee-Rowe (*) [600 MW(t)]	1	FC	E,V,L	SS	5	16.5	Wire mesh	Boric acid, miscellaneous, chemical, and secondary system wastes	Pantex	Modification of original evaporator
Zion 1 & 2 (*) [3250 MW(t)] ea.	4	SU (2 units)	I,H,L	SS	20	18	Wire mesh and trays	Boric acid	Westinghouse	Recirculation pump
		SF	I,H,L	SS	12	35	Wire mesh	Miscellaneous, chemical, detergent, and secondary system wastes	Aqua-Chem	Single-skid mounted, recirculation pump
		SU	I,H,L	SS	15	18	Wire mesh and tray	Miscellaneous, chemical, detergent and secondary system wastes	Westinghouse	Components separated (originally single skid), recirculation pump

[a] Information for plants marked with an asterisk taken from reply to ORNL survey questionnaires; others taken from Final Safety Analysis Report of the plant and open literature reports and thus may not reflect current status.

[b] FC = forced circulation; NC = natural circulation; SF = spray film; SU = submerged U-tube.

[c] E = external; I = internal; H = horizontal; V = vertical; L = long tubes; S = short tubes.

[d] SS = stainless steel.

Table 5. Selected design specifications for evaporators installed in operating (December 31, 1976) boiling water reactors for treating chemical and low-purity wastes[a]

Installation [Capacity]	Number of evaporators	Evaporator type		Materials of construction[d]	Design rating		Entrainment separator	Designer and/or manufacturer	Notes
		Category[b]	Heater[c]		Capacity (gpm)	Pressure (psia)			
Big Rock Point [240 MW(t)]	0								
Browns Ferry 1, 2 & 3 (*) [3293 MW(t)] ea	1[e]				30				Low purity waste only
Brunswick 1 & 2 (*) [2436 MW(t)] ea	2	NC NC	I, V, L I, V, S	304L/316L SS 304L/316L SS	20 50	16 15–16	Wire mesh Wire mesh	Aqua-Chem Swenson	Components separated; good accessibility
Cooper [2381 MW(t)]	1[e]				10			Unitech	
Dresden 1 [700 MW(t)]	0								
Dresden 2 & 3 [2527 MW(t)] ea	2[f]	NC	E, V, L	316L SS	20	45	Baffle and wire mesh	Aqua-Chem	
Duane Arnold (*) [1593 MW(t)]	1[g]								
FitzPatrick [2436 MW(t)]	1	NC	I, V, L	316L SS	20	15	Wire mesh	HPD	
Hatch 1 [2436 MW(t)]	1								
Humboldt Bay [240 MW(t)]	1	NC	I, V, S	SS	1	15	None	Thermovac	Plant shut down indefinitely
LaCrosse (*) [165 MW(t)]	0								
Millstone 1 [2011 MW(t)]	2	NC NC	E, V, L I, V, L	SS SS	25 30			Unitech	30-gpm unit is falling film
Monticello (*) [1670 MW(t)]	0								
Nine Mile Point 1 (*) [1850 MW(t)]	1	FC	E, H, L	304/316L SS	20	15	Wire mesh	HPD	Components separated and shielded
Oyster Creek (*) [1930 MW(t)]	1	NC	E, V, L	SS	15	15	Wire mesh	Swenson	Poor accessibility to unit
Peach Bottom 2 & 3 (*) [3293 MW(t)] ea	0								
Pilgrim 1 [1998 MW(t)]	1	SF	I, H, L	SS	15	16	Wire mesh with spray nozzles		Evaporator not in service; temporarily replaced with filtration and ion exchange
Quad Cities 1 & 2 [2511 MW(t)] ea	0								
Vermont Yankee (*) [1593 MW(t)]	0								

[a] Information for plants marked with an asterisk taken from reply to ORNL survey questionnaires; others taken from Final Safety Analysis Report of the plant and open literature reports and thus may not reflect current status.

[b] FC = forced circulation; NC = natural circulation; SF = spray film; SU = submerged U-tube.

[c] E = external; I = internal; H = horizontal; V = vertical; L = long tubes; S = short tubes.

[d] SS = stainless steel.

[e] To be installed.

[f] Shared (one on standby).

[g] Now installed for future use.

provide an optionally available increase in evaporation capacity should the need arise. At least one plant (Yankee-Rowe) uses a single evaporator for all volume reduction functions.

6.1.1 Boron recycle evaporators

The 300-series stainless steels have apparently been satisfactory materials of construction for treating borated coolant water in the pH

Table 6. Performance of evaporators used in light water reactor power plants

Installation [Capacity] Reactor type	Evaporator		Stream treated	Evaporator capacity (gpm)				Operating time (%)	Maintenance time (%)	Feed				Antifoam agent	Volume reduction (feed/thick liquor)	Notes
	Category[a]	Designer and/or mfgr.		Design	Operating					pH	Cl (ppm)	Pretreatment				
					Max	Min	Avg					Filtered	Degassed			
Beaver Valley 1 [2660 MW(t)] PWR	FC	Stone & Webster	Miscellaneous, chemical, and secondary system wastes	6	5				See comment			No	No	No		Loss of capacity due to solidification in thick liquor pump and lines.
Brunswick 1 & 2 [2436 MW(t)] ea. BWR	NC	Aqua-Chem	Chemical and low-purity wastes	20				3–8 (5 avg)				No	No	Betz HT		Problems with entrainment, foaming, instrumentation, and plugged tubes.
	NC	Swenson	Chemical and low-purity wastes	50				55–82 (68 avg)				No	No	Betz HT	20–80	Problems with entrainment, foaming, and extensive corrosion (evaporator will be replaced).
Cook 1 [3250 MW(t)] PWR	SU	Westinghouse	Miscellaneous, chemical, detergent, and secondary system wastes	2	1.5	0.5	1.3	72.2	2.9	7.5–8.3 (8.0 avg)	10–80 (15 avg)	Yes	No	Dow H-10	20–100 (50 avg)	Poor condensate quality. NaOH added for pH control.
Crystal River 3 [2452 MW(t)] PWR	SU	(AMF)-Riley Beaird	Miscellaneous, chemical, and secondary system wastes	20	20	1	12.5	10–20 (15 avg)				No	No	Dow	10 avg	Components not readily accesible for decontamination and maintenance.
Ft. Calhoun [1420 MW(t)] PWR	SF	Aqua-Chem	Miscellaneous, chemical, detergent and secondary system wastes	17	14			44–66	8–9			Optional	No	GE		Gas stripper inoperable, low capacity due to plugging of spray nozzles, poor condensate quality, highly congested component arrangement. $Na_2S_2O_3$ is added for iodine control.
Maine Yankee [2440 MW(t)] PWR	FC	Stone & Webster	Boric acid	25								Yes	Yes	No		No corrosion problems to date.
	FC	Stone & Webster	Miscellaneous, chemical, and secondary system wastes	6			5–6							Ameril	100	Performance as expected.
Nine Mile Point 1 [1850 MW(t)] BWR	FC	HPD	Chemical wastes	20	20	5	15	30–60		6–9		No	No	No	15	Only casual operator attention is needed.
			Low-purity waste	20	20	5	15	40		6–9		Yes	No	Dow B	400	This is the same evaporator that is used for chemical waste. Na_2HPO_4 is added for chloride control.
Oconee 1, 2 & 3 [2568 MW(t)] ea. PWR	SF	Aqua-Chem	Miscellaneous, chemical, and secondary system wastes	7.5	5	2.5							No	Yes	10	System is being modified.
	SU	Westinghouse	Same as above	15	15	10	12	82						Yes	10	DF approximately a factor of 10^3 less than design DF.
Oyster Creek [1930 MW(t)] BWR	NC		Chemical and low-purity wastes	[illegible]	10	6	8			8–9.5					60	Tube plugging led to reduced waste processing.
Palisades [2212 MW(t)] PWR	SU	(AMF)-Riley Beaird	Boric acid and reactor makeup quality waste	20			20	20		5.1	0–0.4 (0.3 avg)	Yes	No	Yes	14	High degree of operator attention required, maintenance time is high.
	SU	(AMF)-Riley Beaird	Miscellaneous, chemical, and secondary system wastes	20			15	20		5.75–7.2		Yes	No	Yes	16	High degree of operator attention required; maintenance time is high. NaOH is added for pH control.
St. Lucie 1 [2570 ME(t)] PWR	NC	Aqua-Chem	Boric acid	20	20	2	10	~100	2	8.5 avg	35 avg	Yes	Yes	No	16–18 (17 avg)	Requires fairly close operator attention for satisfactory performance.

Table 6 (continued)

Installation [Capacity] Reactor type	Evaporator		Stream treated	Evaporator capacity (gpm)				Operating time (%)	Maintenance time (%)	Feed				Antifoam agent	Volume reduction (feed/thick liquor)	Notes
	Category[a]	Designer and/or mfgr.		Design	Operating					pH	Cl (ppm)	Pretreatment				
					Max	Min	Avg					Filtered	Degassed			
Three Mile Island 1 [2535 MW(t)] PWR	**SU**	**(AMF)-Riley Beaird**	Miscellaneous, chemical, and secondary system wastes	12.5				48				Optional	No	Dupont		Components are not easily accessible; excessive operator attention is required.
Turkey Point 3 & 4 [2200 MW(t)] ea. PWR	**NC**	**Aqua-Chem**	Boric acid	5			4	55				Yes	Yes	No	18–20	Both boric acid evaporators meet design specifications.
	SU	**Westinghouse**	Miscellaneous, chemical, detergent and secondary system wastes	15			12	55				Yes	Yes	Optional	18–20	Both waste evaporators perform below design specifications. NaOH can be added for pH control.
Yankee-Rowe [600 MW(t)] PWR	**FC**	**Pantex**	Boric acid, miscellaneous, chemical, and secondary system wastes	5	5	2.5	5	20–33 (25 avg)	<1	6–10 (8 avg)		No	No	No	20–100 (50 avg)	Drew Chemical Corp. L-113 antifoam being tested.
Zion 1 & 2 [3250 MW(t)] ea. PWR	**SF**	**Aqua-Chem**	Miscellaneous, chemical, detergent, and secondary system wastes	12			~12	92	8	7.3–8.4		No	No	Calgon C1	75–100	Components are not easily accessible.
	SU	**Westinghouse**	Same as above	15	10	6	8	82	16	7.3–8.4		No	No	Calgon C1	50–1000	Performs below design specification; condensate quality varies randomly; constant operator attention required.

[a] FC = forced circulation; NC = natural circulation; SF = spray film; SU = submerged U-tube.

4.5 to 10.2 range. In general practice, the feed to the boron recycle evaporator has nearly always been filtered and degassed at some prior point in the recycle process. The survey indicated that boric acid evaporators of all types perform about at or near design specifications and, at least, have been adequate for their intended purpose. Volume reductions of 10 to 20 are reported to be readily attainable while operating close to design capacity. One of the main problems mentioned was the solidification of boric acid at the bottom of the evaporator and in the concentrated boric acid transfer lines. The usual remedies suggested were avoidance of bottoms concentrations greater than ∿6 wt % boric acid and heat tracing of the transfer lines. The other frequently occurring problem reported was that skid-mounted units complicated maintenance procedures because components (e.g., heaters, pumps, instrumentation, etc.) were not readily accessible. Some plants are now separating components and isolating them with shielding.

6.1.2 Chemical and miscellaneous waste evaporators

At PWRs, the chemical wastes contain varying amounts of boron (as boric acid or borate salts) and, in some cases, sodium and sulfate from the regeneration of spent ion-exchange resins. Additionally, ammonium ion may be present in relatively large amounts (i.e., several hundred or thousand ppm). These are the major differences between PWR and BWR chemical wastes. The miscellaneous waste from a PWR contains varying amounts of boron, ammonia, and hydrazine or other organic reducing agents which are not normally present in BWR low-purity wastes. Otherwise, the miscellaneous (PWR) and low-purity (BWR) wastes are quite similar. The waste evaporators at some PWRs have operated below design specifications. A contributing factor is the wide variability of the feed composition and the attendant difficulty of regulating pH. Volume reduction factors usually fall in the 10 to 100 range but may be as small as 3 or as large as 1500, depending on what is present in the stream at the time. Inadequate capacity (undersizing), corrosion, and plugging of the heater tubes have been the greatest problems encountered with waste evaporators at PWRs. Attempts to solve tube plugging problems have included such approaches as replacement of the original stainless steel tube bundle with a bundle of larger diameter tubes or with tubes fabricated from a highly corrosion-resistant alloy such as Inconel 625 (when fouling due to corrosion was suspected to be the cause of the plugging). Preventive maintenance in the form of scheduled periodic cleaning has also been implemented at some plants. The problem of an undersized waste evaporator has also been approached in several ways. Most plants that had small (i.e., less than 10-gpm capacity) evaporators as original equipment have augmented their waste evaporation systems either by addition of another evaporator of larger capacity or by modifying the inadequate unit to increase its capacity. A few stations in these circumstances have abandoned waste evaporation in favor of ion exchange, and they do not regenerate the resins. The possibility of corrosion occurring in LWR waste evaporators has prompted many utilities with PWRs now under construction to order Incoloy 825, Inconel 625, and/or Alloy 20 as materials of construction. This trend is shown by comparing the data in Table 4 with that in Table B-1 in Appendix B. Further comparison of these tables also shows a general leaning toward installation of more evaporators of larger size in the next generation of PWR nuclear power plants.

6.2 Evaporator Applications in BWRs

Some of the newer BWRs that use only powdered-resin demineralizers for stream cleanup do not have evaporators. The powdered resins are not regenerated, and apparently the amount of chemical waste at these plants is therefore not sufficient to make evaporation prior to solidification economically advantageous. Some operating BWRs of this type, however, have installed, or are planning to install, evaporators to treat their low-purity wastes and thus lower the radioactivity in the liquids discharged from the plant. Most BWRs that do have resin regenerant solutions also have evaporators for concentrating these chemical wastes. Consequently, they also use them for treating their low-purity waste stream. The status of evaporation at some of these operating BWR plants is shown in Table 5. In evaporating BWR chemical wastes, volume reductions of 15 to 20 are usually achieved, which compares well with those achieved for similar wastes at PWRs. The low-purity wastes can usually be volume-reduced by factors ranging from 80 to 400, which is also in line with volumes reported for PWR miscellaneous wastes. The performance of BWR waste evaporators is about the same as that of the miscellaneous waste evaporators at PWRs (see Table 6).

In the past, stress corrosion has been the dominant evaporator problem at BWRs, and several plants have long since replaced their original evaporation equipment. Stainless steel still seems to be the construction material most often used for evaporators at operating BWR plants, but a comparison of the data summarized in Table 5 with that in Table B-2 in Appendix B again points up the trend toward Incoloy 825 or Alloy 20 in this application. Another problem has been the excessive maintenance experienced with canned-motor pumps when used in handling viscous, gritty concentrates. Replacing them with open-impeller centrifugal and axial-flow (propeller) types has largely alleviated the problem. Such experiences with canned-motor pumps have been observed not only in BWRs but also in PWRs, and in the latter they have been replaced with these other types.

7. DECONTAMINATION FACTOR

The effectiveness of unit operations such as centrifugation, evaporation, filtration, ion exchange (demineralization), and reverse osmosis for reducing the radioactivity in process streams within, or effluent streams from, nuclear installations is usually expressed in terms of the decontamination factor (DF) for each isotope of concern and/or gross activity.

7.1 Definition of Decontamination Factors

A comparison of the amount of a substance in the thick liquor from an evaporator to the amount of that substance (on the same basis) in the condensate is defined as an equipment DF. This ratio is also called an evaporator DF and sometimes a separation factor. A comparison of the amount of a substance in the feed to the amount of that substance (on the same basis) in the condensate is defined as a system DF. This ratio may also be called a process DF. The interrelationships between these various DFs for continuous, batch, and semicontinuous modes of evaporator operation are derived in ref. 7. In nuclear installations, DFs are usually based on radioactivity, but on occasion, a stable substance (e.g., chloride or silica) may be the item of interest.

The instantaneous system decontamination factor across an evaporator is defined as the ratio of the concentration of a given component in the feed at any time to the concentration for the same component in the condensate at that time. In other words, the instantaneous system DF, $(DF)_{si}$, is given by the expression

$$(DF)_{si} = C_f/C_c \ , \qquad (1)$$

where

C_f = the amount (mass or radioactivity) of a specified component in the feed per unit volume at time t and

C_c = the amount of the specified component in the condensate per unit volume at time t.

The time- (or volume-) average system DF is defined as the ratio of the total amount of a given component in the cumulative evaporator feed to the total amount of the same component in the cumulative condensate over a prescribed period of time (e.g., the time to empty a feed tank or the time to fill a condensate tank). In other words, the time-average system DF, $(DF)_{st}$, is given by the expression

$$(DF)_{st} = A_f/A_c \ , \tag{2}$$

where

A_f = the total amount (mass or radioactivity) of a specified component in the feed over a period of time Δt and

A_c = the total amount of the specified component in the condensate over the period of time Δt.

Obviously, one or two values of $(DF)_{si}$ may not represent the average behavior of an evaporator. However, if values of $(DF)_{si}$ are available as a function of time, $(DF)_{st}$ may be obtained by integration (most likely graphical) of an expression of the form

$$(DF)_{st} = \frac{\int_0^{\Delta t} [(DF)_{si}] \, dt}{\Delta t} \ , \tag{3}$$

where $[(DF)_{si}]$ represents $(DF)_{si}$ as a function of time. More often the assumption is made that the number of observations of $(DF)_{si}$ is sufficiently large so that

$$(DF)_{st} = (\overline{DF})_{si} = \frac{1}{n} \sum_{j=1}^{n} (DF)_{si} \ , \tag{4}$$

where

$(\overline{DF})_{si}$ = the mean value of $(DF)_{si}$,

n = the number of observations, and

j = an integer.

The standard deviation of $(DF)_{si}$, σ, is given by

$$\sigma = \left\{ \frac{1}{n-1} \left[\sum_{j=1}^{n} (DF)_{si}^{2} - \frac{1}{n} \left(\sum_{j=1}^{n} (DF)_{si} \right)^{2} \right] \right\}^{1/2} , \qquad (5)$$

and the standard error of the mean, $\bar{\sigma}$, is given by

$$\bar{\sigma} = \sigma / n^{1/2} . \qquad (6)$$

With the assumption of proper sampling and analyses, the DF of an evaporator should, in theory, be one or greater. However, $(DF)_{si}$ may be less than one if, for example, the condensate sample was taken during or shortly after a splashover or a period of excessive foaming. Such a condensate sample could be more like the liquid in the evaporator and thus more concentrated than the feed. Values of $(DF)_{st}$ less than one are possible if large amounts of material previously deposited on the walls of the flash chamber or in the entrainment separators are washed off and carried into the condensate. Reference 48 lists seven situations that can lead to excessive entrainment losses (i.e., low DFs):

1. Improper levels. If levels are either too high or too low, depending on the type of evaporator involved, entrainment losses can increase greatly.

2. Evaporator overloaded. The evaporator is operated at rates beyond its design capacity.

3. Entrainment separator plugged up or damaged. The separator operates at flow conditions other than those for maximum effectiveness.

4. Separator drains plugged or not properly sealed. The separator cannot function as designed.

5. Fluctuating flash chamber pressures. This is a very common cause of severe entrainment. When the pressure increases, boiling stops temporarily and the temperature of the pool of liquid in the evaporator increases. When the pressure starts to decrease, the heat

stored in the pool of liquid is suddenly released and the evaporation rate is momentarily much higher than usual. In the case of foamy liquids, the liquid can foam over with large losses.

6. Abnormally foamy liquids. Sometimes antifoam agents will keep such liquids under control. Fluctuating flash chamber pressures, as described above, are especially troublesome with such liquids.

7. Air leaks under the liquid level. This can be very troublesome with foamy liquids. Air leaks in the discharge piping can interfere with the discharge of liquid from the evaporator, which can lead to high levels with attendant losses.

7.2 Some Reported DFs

The system DFs reported in this survey are presented in Figs. 12 and 13. Figure 12 gives the DFs for boron recycle evaporators in PWRs. Figure 13 gives the DFs for waste evaporators in both PWRs and BWRs. The mean values for the DFs were calculated using Eq. (4). As described in Sect. 4, for purposes of comparing DFs by evaporator type, evaporators are categorized as natural circulation (NC), forced circulation (FC), spray film (SF), and submerged U-tube (SU) and are identified as such in Tables 4-6 as well as Tables B-1 and -2 (in Appendix B). The total number of each type (for the plants reporting in this survey) are listed in Table 7. To broaden the data base for comparison of DFs, the evaporators in the previous ORNL survey[7] were similarly categorized. With this broadened data base, the mean (average) system DFs for all evaporators reported and for each of the four types were calculated using Eq. (4). Undoubtedly, many of the DFs reported are time average, and not instantaneous, and therefore weighting factors should be applied. However, the lack of such complete DF data precluded weighting, and all numbers are treated equally in this analysis. The results are listed in Table 7. These results show that an average system DF of about 10^4 can be expected for nonvolatile fission and corrosion products in the NC and FC types, while an average system DF of about 10^3 can be expected for iodine. They further show that an average system DF of slightly over

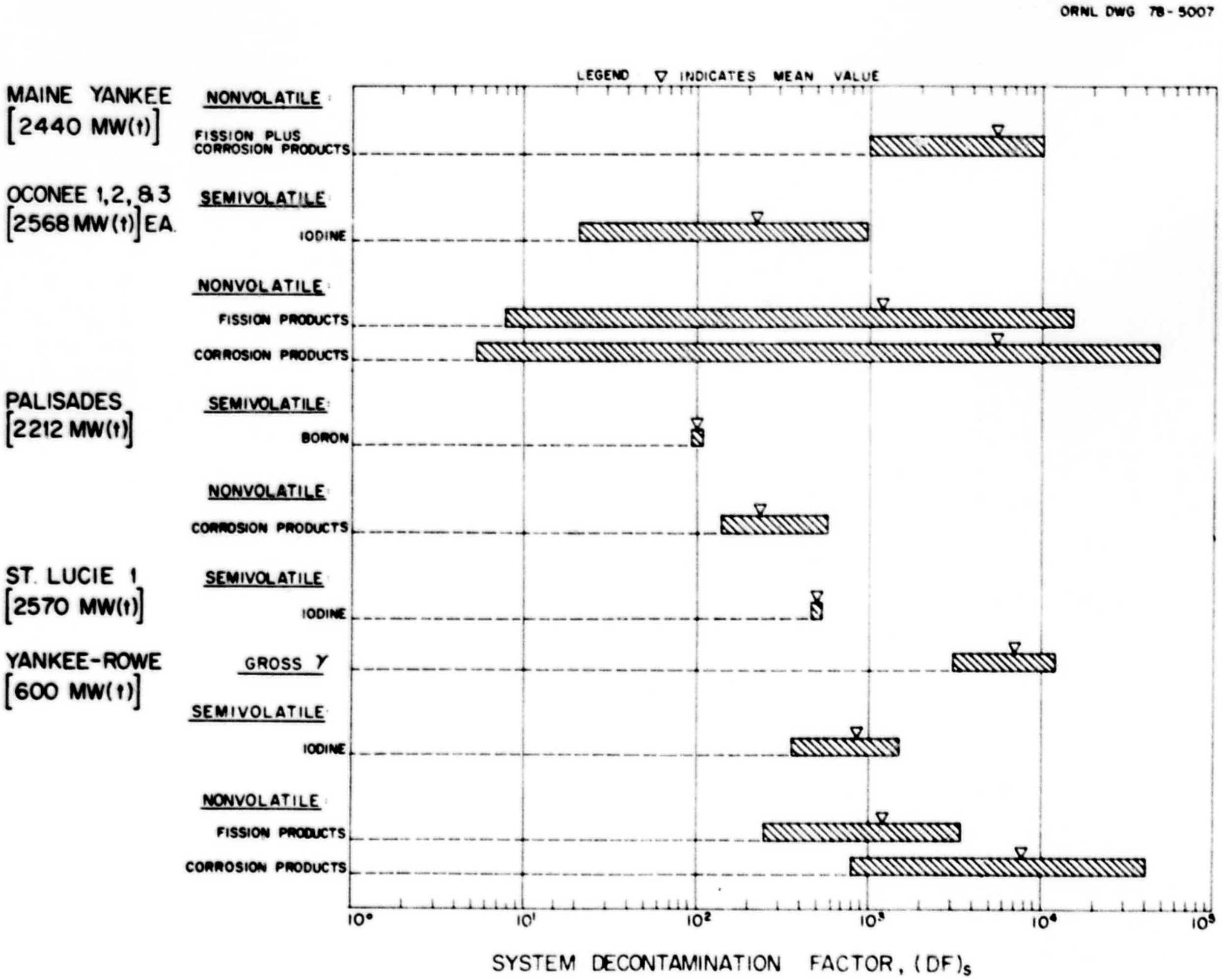

Fig. 12. Comparison of decontamination factors for several boron recycle evaporators at PWR nuclear power plants.

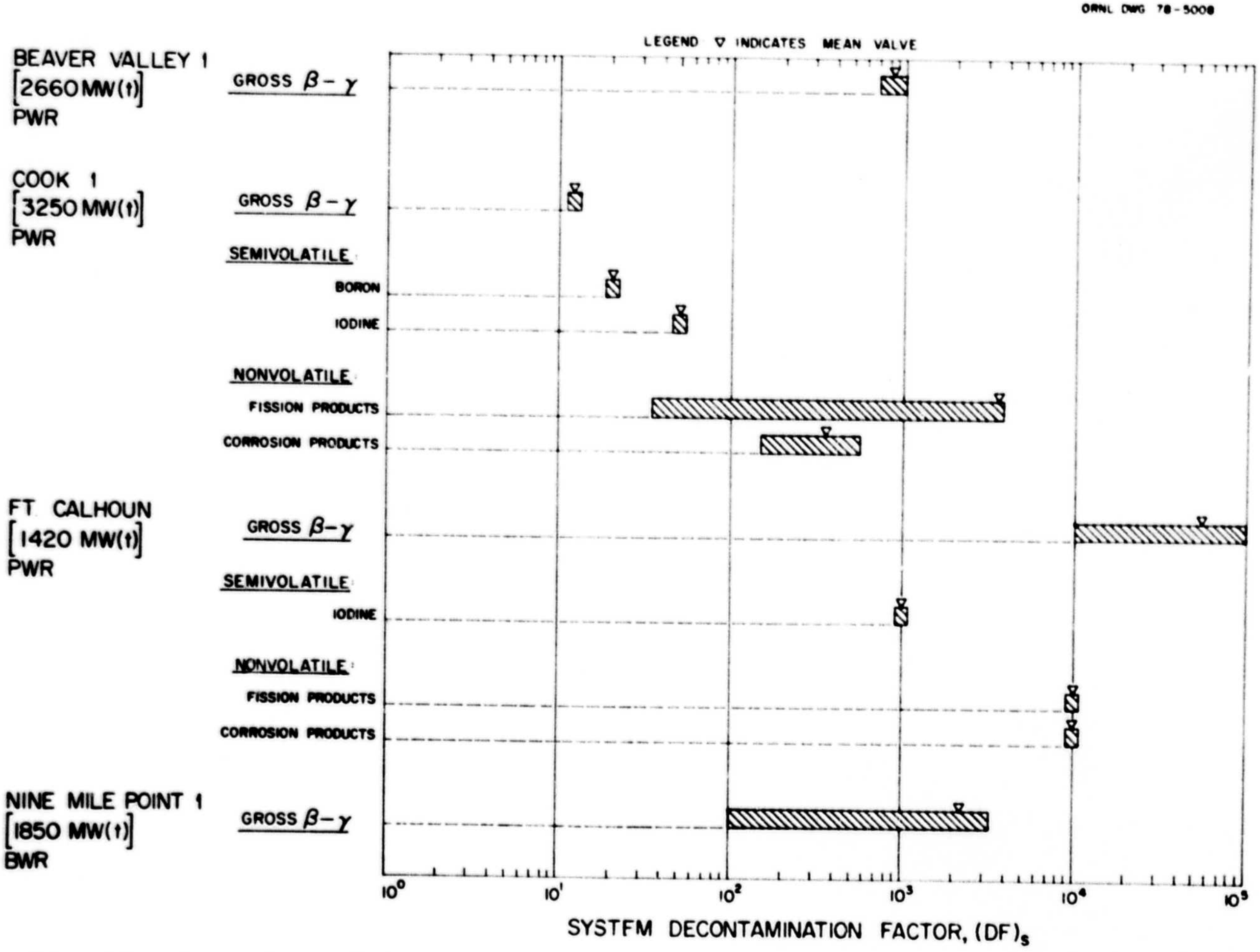

Fig. 13. Comparison of decontamination factors for several radwaste evaporators at LWR nuclear power plants.

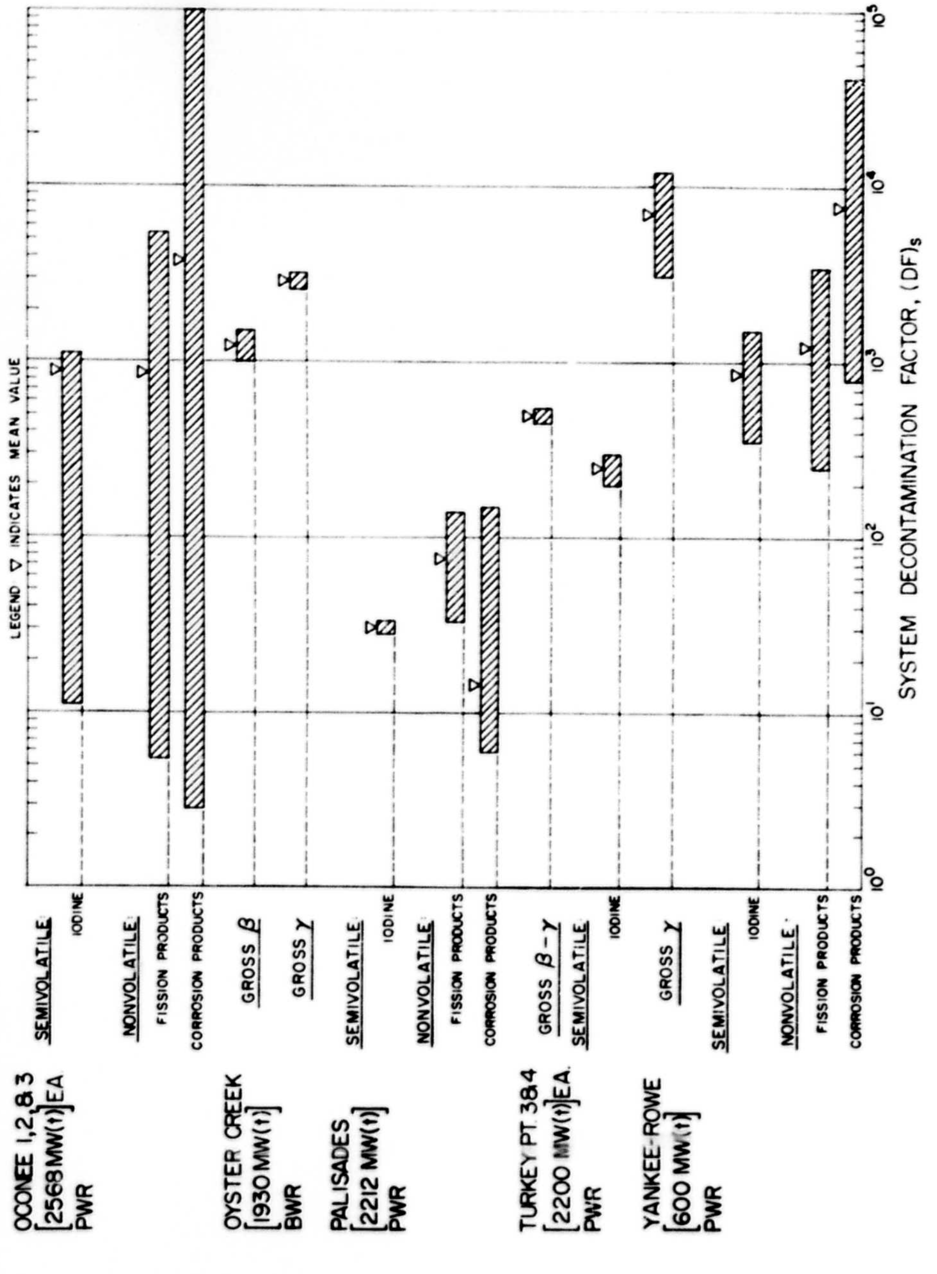

Fig. 13 (continued)

Table 7. A comparison of the number of, and decontamination factors for, several types of evaporators used or to be used in light water reactor power plants

Type of reactor	Number of evaporators[a]				
	Total	Natural circulation	Forced circulation	Spray film	Submerged U-tube
Boiling water reactors:					
Operating (19 plants containing 25 reactors)[b]	15[c]	8	2	1	0
Future (8 plants containing 13 reactors)	11[d]	0	6	0	2
Pressurized water reactors:					
Operating (24 plants containing 32 reactors)[e]	56[f]	4	11	5	31
Future (17 plants containing 32 reactors)	35[g]	0	19	0	16

Type of activity	Mean decontamination factor[h]				
	Overall	Natural circulation	Forced circulation	Spray film	Submerged U-tube
Gross β-γ	2.1E + 04	4.2E + 04	1.6E + 04	3.0E + 03	9.0E + 03
Iodine	9.9E + 02	1.1E + 03	1.6E + 03	3.2E + 02	7.0E + 02
Fission products	2.3E + 04	4.3E + 04	1.3E + 04	1.6E + 03	2.8E + 03
Corrosion products	1.1E + 04	2.5E + 04	1.4E + 04	3.3E + 03	3.3E + 03

[a] Information taken from replies to ORNL questionnaires; since replies were not received from all plants and some replies were not complete, the data is truncated.
[b] Seven plants reported having no evaporator.
[c] No description of type given for four evaporators.
[d] No description of type given for three evaporators.
[e] Two plants reported having no evaporator.
[f] No description of type given for five evaporators.
[g] See note a; in particular several PWRs did not mention and/or describe boric acid evaporators.
[h] The mean DF was calculated as described in this section using the DF data from the previous ORNL survey as well as from this survey.

10^3 can be expected for nonvolatile fission and corrosion products in the SF and SU types, while an average system DF of about 5×10^2 can be expected for iodine.

In Table 8, the mean DFs calculated with the DFs from both surveys are grouped according to function (boron recycle or waste) and reactor type (PWR or BWR). The standard deviations and standard error of the mean for these values are also given in Table 8. These results indicate that the waste evaporators in PWR and BWR plants give similar DFs. However, they also show that in PWR plants the boron recycle evaporator can give DFs that are lower than those of the waste evaporator by a factor of up to 10 for nonvolatile fission and corrosion products and by about 20% for iodine.

Table 8. Mean, standard deviation, and standard error of the mean for the decontamination factors (DFs) obtained from operating light-water reactor power plants[a]

Reactor type	BWRs plus PWRs		BWRs	PWRs		
Evaporator function	Waste	Waste + Recycle	Waste	Waste + Recycle	Waste	Recycle
Gross $\beta - \gamma$						
mean DF	2.2E + 04	2.1E + 04	2.2E + 04	2.0E + 04	2.3E + 04	4.7E + 03
standard deviation	6.1E + 04	5.8E + 04	6.7E + 04	5.3E + 04	5.7E + 04	3.3E + 03
standard error of mean	8.1E + 03	7.5E + 03	1.4E + 04	8.7E + 03	9.9E + 03	1.5E + 03
number of points	56	61	23	38	33	5
Iodine						
mean DF	1.1E + 03	9.9E + 02	1.1E + 03	9.6E + 02	1.1E + 03	8.3E + 02
standard deviation	1.1E + 03	1.1E + 03	1.1E + 03	1.1E + 03	1.1E + 03	1.2E + 03
standard error of mean	2.3E + 02	1.9E + 02	4.1E + 02	2.2E + 02	2.9E + 02	3.6E + 02
number of points	23	33	7	26	16	10
Fission products						
mean DF	3.2E + 04	2.3E + 04	4.3E + 04	1.5E + 04	2.5E + 04	1.9E + 03
standard deviation	1.2E + 04	1.0E + 05	1.3E + 05	8.7E + 04	1.2E + 05	2.3E + 03
standard error of mean	1.8E + 04	1.2E + 04	2.9E + 04	1.2E + 04	2.2E + 04	4.8E + 02
number of points	49	71	21	50	28	22
Corrosion products						
mean DF	1.3E + 04	1.1E + 04	2.5E + 04	8.3E + 03	9.3E + 03	6.4E + 03
standard deviation	3.8E + 04	3.2E + 04	6.3E + 04	2.1E + 04	2.5E + 04	3.3E + 03
standard error of mean	5.1E + 03	3.7E + 03	1.7E + 04	2.6E + 03	3.9E + 03	7.1E + 02
number of points	56	78	14	64	42	22

[a] The mean, standard deviation, and standard error of the mean were determined using the equations presented in this section.

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10. GLOSSARY

Batch evaporation is a mode of operation in which the evaporator initially contains the entire quantity of liquid to be evaporated. Vapor is removed until the thick liquor reaches the desired concentration, at which time the liquor is removed.

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.

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.

Body is a word used to denote the unit in which vapor-liquid separation is accomplished in an evaporator. It is also used to denote the minimum units needed for an evaporator, that is, one heating element and one flash chamber.

Bottoms is used synonymously with thick liquor (qv).

Calandria is a term used to denote the unit in which heat transfer takes place in an evaporator. It is also used to describe a short-tube, vertical evaporator which was once so common that it was called a standard evaporator.

Capacity is defined as the weight or mass of liquid evaporated per unit of time.

Circulation operation signifies that the feed mixes with liquid that has passed through the heater tubes one or more times, and the mixture then passes again through the tubes.

Conductivity, unless otherwise specified, is taken to mean electrical conductivity (qv).

Continuous evaporation is a mode of operation in which the feed and thick liquor flows are constant and process conditions are constant with time; that is, the operation is at steady state.

Crud burst is a phrase used to depict the spurious quantities of nondescript solids that can appear when the operating parameters (flow rate, temperature, pH, etc.) of a system are changed. Frequently, but not always, it follows a sudden or drastic change in system operating parameters.

Crystallization is the separation of a solid crystalline phase from a liquid phase by cooling, evaporation, or precipitation caused by the addition of a third substance.

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} (Bq = 2.7×10^{-11} Ci).

Distillate is a word frequently used to describe the condensed vapor from an evaporator.

Drips are the steam condensates from a heater.

Electrical conductivity is a loosely used term that generally means specific electrical conductivity (qv).

Entrainment is liquid suspended in the vapor as fine droplets that are carried along with the rising vapor stream.

Equipment decontamination factor (DF) is defined as the ratio of the concentration of a component in the thick liquor to its concentration in the condensate.

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

Evaporator DF is used synonymously with equipment DF (qv).

External heater denotes a heat-transfer unit that is separated from the evaporator flash chamber.

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

Flash chamber is a term used to denote the unit in which vapor-liquid separation is accomplished in an evaporator.

Foam is a mass of stable bubbles formed in or on the surface of the thick liquor.

Forced-circulation evaporators are those in which movement of liquid past the heating surface is induced by mechanical means such as a pump or propeller.

Fouling is the formation of deposits other than salt or scale and may be due to corrosion, solid matter entering with the feed, or deposits formed by the condensing vapor.

Heater is used synonymously with heating element (qv).

Heating element is a term used to denote the unit in which heat transfer (exchange) takes place in an evaporator.

Instantaneous system decontamination factor (DF) is defined as the ratio of the concentration of a given component in the feed at any time to the concentration for the same component in the condensate at that time.

Internal heater denotes a heat-transfer unit that is an integral part of the evaporator flash chamber.

Natural-circulation evaporators are those in which movement of liquid past the heating surface is induced by gravity or the density variations brought on by boiling.

Once-through operation signifies that the feed liquor passes through the heater tubes only once and leaves the evaporator as thick liquor.

Overhead is a word frequently used synonymously with condensate or distillate (qv).

Process DF is used synonymously with system DF (qv).

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.

Salting is the growth on body and heating-surface walls of a material having a solubility that increases with increase in temperature.

Scaling is the deposition and growth on body walls, and especially on heating surfaces, of a material undergoing an irreversible chemical reaction in the evaporator or having a solubility that decreases with an increase in temperature.

Semibatch evaporation is used synonymously with semicontinuous evaporation (qv).

Semicontinuous evaporation describes the gamut of operational modes between batch and continuous. Commonly it describes a mode of operation in which feed is continually added to maintain a constant level in the evaporator with no thick liquor being removed. When the thick liquor reaches the desired concentration, the entire charge is removed.

Separation factor is used synonymously with equipment DF (qv).

Specific electrical conductivity of an electrolyte is defined as the reciprocal of the electrical resistance (ohms) of the electrolyte contained between parallel electrodes of 1-cm^2 cross-sectional area set 1 cm apart. The units are mhos (i.e., ohms^{-1}) per cm.

Splashover consists of the carry-over of large parcels of thick liquor into the condenser.

Steam economy is defined as the mass of liquid evaporated per mass of steam used.

Submerged tube describes an evaporator in which the heater is placed far enough below the liquid level or return line to the flash chamber to prevent boiling in the tubes.

Surface tension is the property, due to molecular forces, existing in the surface film of all liquids which tends to contract the volume into a form with the least surface area. The particles in the surface film are inwardly attracted, thus resulting in tension.

System decontamination factor (DF) is defined as the ratio of the concentration of a component in the feed to its concentration in the condensate.

Time-average system decontamination factor (DF) is defined as the ratio of the total amount of a given component in the cumulative evaporator feed to the total amount of the same component in the cumulative condensate over a prescribed period of time.

Thick liquor is a term applied to the concentrated solution or slurry removed from an evaporator.

Thin liquor is a term applied to the solution or slurry fed to an evaporator.

Vapor head is used synonymously with flash chamber (qv).

Viscosity is the physical property that characterizes the resistance offered by a fluid (gas or liquid) to flow. It is a measure of the combined effects of adhesion and cohesion.

Volume-average DF is equivalent to a time-average DF (qv).

APPENDIX A. ELEMENTS OF EVAPORATION

APPENDIX A. ELEMENTS OF EVAPORATION

In this appendix several modes of operating an evaporator and several factors that can have an effect on the performance of an evaporator are discussed (following ref. 7) in terms of generally accepted evaporator technology.

A.1 Modes of Evaporator Operation

Evaporators are operated in several modes: batch and continuous, which are well defined in chemical engineering terminology, and semicontinuous, which includes all modes of operation other than batch or continuous. Three modes of evaporator operation – batch, semicontinuous (or semibatch), and continuous – are defined and described below.

A.1.1 Batch operation

In batch operations, feed and product flows are intermittent, process conditions are generally programmed with time, and steady-state conditions are never attained. In batch operation, the quantity of solution or slurry to be evaporated at one time is charged to the evaporator; boiling is initiated; and the vapors are then continuously removed, condensed, and collected. Evaporation is continued until the desired amount of condensate (often called overhead or distillate) has been collected or until the thick liquid (often termed bottoms or concentrate) reaches the concentration, density, or viscosity desired. The thick liquor is then removed from the evaporator. This mode of operation is frequently used in the laboratory or when a relatively small volume of material is to be concentrated.

A.1.2 Continuous operation

In continuous operations, feed and product flows are constant and process conditions are constant with time. The operation is at steady state. Continuous operation is highly desirable since control is easy once steady state has been achieved; however, it requires a large or continous supply of feed with a uniform composition (e.g., desalination).[52]

A.1.3 Semicontinuous operation

In a semicontinuous evaporation, a predetermined quantity of solution or slurry is charged to the evaporator; boiling is initiated; and vapors are then continuously removed, condensed, and collected. Feeding of solution or slurry to the evaporator is continued at a rate approximately equal to the rate at which condensate is removed, that is, at a rate to maintain a constant liquid volume in the evaporator. Evaporation is continued until the feed is exhausted or a desired concentration of thick liquor is achieved. The thick liquor is then removed from the evaporator. This mode of operation is widely used at nuclear installations. It is often described as a batch operation or semibatch operation. However, since it is neither a true batch (feed and condensate flows are constant) nor a true continuous operation (thick liquor concentration is changing with time), semibatch or semicontinuous seems to be a more descriptive name. In one variation of this mode, only a portion of the thick liquor is removed and the feed is restarted. This seems to aid in reestablishing boil-off without too much difficulty (i.e., excessive foaming and splashing). In another variation, after partial concentration is achieved in the semicontinuous mode, the feed is stopped and the final concentration is achieved in a batch mode. This is reported[12] to reduce the potential for corrosion and/or fouling.

A.2 Factors Influencing the DFs of Evaporators

In evaporating radioactive solutions, effective entrainment separation is required to avoid contaminating the condensate. Equally important in evaporating radioactive liquids is operation under conditions (pH, redox, temperature) to suppress the volatilization of radioactive materials such as iodine and some organics that can have high vapor pressures. Evaporators can separate water from solids very effectively, and a system decontamination factor of 10^4 to 10^5 is generally expected for a single-effect evaporator separating water from a nonvolatile solute. Decontamination factors are decreased by four basic factors: entrainment, splashover, foam, and volatilization of solute.

A.2.1 Entrainment

Entrainment is liquid suspended in the vapor as fine droplets that are carried along with the rising vapor stream. The extent of entrainment losses from an evaporator depends, for the most part, on the vapor velocity and the size, size distribution, and number of the droplets.[53,54] The larger droplets are a major source of entrainment losses unless they settle back into the liquid or are removed by entrainment separators (deentrainment devices). Evaporators generally have devices incorporated or attached to remove the entrained larger droplets that do not settle back. Droplets appear to be formed[53-55] in two ways: the first is that a steam bubble rises up through the boiling liquid and bursts at the liquid surface, scattering droplets whose diameters are on the order of a few micrometers; and the second is that the rarefaction (partial vacuum) caused by the passage of the bubble through the surface causes droplets of a few hundred micrometers to be jetted into the vapor space from the surface of the liquid. The size, number, and rate of ascent of vapor bubbles in the boiling liquid and the physical properties of the liquid determine the size, size distribution, and number of droplets formed. A droplet can fall or settle back into the liquid if its terminal falling velocity is greater than the velocity of the rising vapor. Evaporators usually have large flash chambers so that the vapor velocity will be low and the larger droplets can settle back. Entrainment losses can be increased by flashing, which is the sudden production of copious quantities of steam bubbles. It is caused by incidents such as introducing feed that is above its boiling point or poor vacuum control, that is, sharply varying vacuum.

At higher boilup rates, entrainment increases and thus the DF generally decreases with increasing boilup.[18,56] These results could imply that at lower boilup rates the DF would be higher. However, at very low boilup rates the DF decreases with decreasing boilup rate.[23,57] Smaller vapor bubbles produced by gentle boiling lead to the production of smaller droplets that are readily carried by the ascending vapor. For an evaporator without deentrainment devices, an optimum boilup rate for minimum entrainment and maximum DF exists at a mass vapor velocity of around 20 to 40 lb ft^{-2} hr^{-1} (100 to 200 kg m^{-2} hr^{-1}), where the velocity is calculated at the largest horizontal cross-sectional area for vapor flow.[57] This optimum for the evaporator alone should be between the two regimes: (1) low boilup with small droplets that can be entrained by the low vapor velocities concomitant with low boilup, and (2) high boilup with larger droplets and high vapor velocities capable of carrying them. However, the extent of entrainment losses from entrainment separators such as wire mesh, cyclones, and trays depends, for the most part, on the vapor velocity and the size, size distribution, and number of the droplets. The desired optimum is the point at which the product of the DFs for the evaporator and entrainment separators is at a maximum. This optimum does not necessarily occur at the boilup rate at which the evaporator DF is a maximum. The overall DF for the evaporator plus deentrainment devices may differ widely from the DF for the evaporator alone.

A.2.2 Splashover

Splashover consists of the carry-over of large parcels of thick liquor into the condenser. It occurs at very high boilup rates when boiling becomes violent and erratic. Splashover losses are usually insignificant if sufficient distance[21] between the surface of the boiling liquid and the outlet of the flash chamber is provided, so that the parcels fall back before reaching the outlet, or if an impingement baffle covering the outlet of the flash chamber is provided to deflect the parcels downward. A single large splashover can ruin a large volume of otherwise acceptable condensate.

A.2.3 Foam

Foam is a mass of stable bubbles formed in or on the surface of the thick liquor. Among the causes of foam in an evaporator are traces of organics, finely divided solids, and dissolved gases. It leads to an increase in entrainment by raising the effective liquid level, which decreases the amount of deentrainment space, and by supplying stable bubbles that the vapor can carry. Thus, it can lower the decontamination factor markedly. Foam control measures that are sometimes effective include: the addition of chemical antifoam agents, such as the silicone preparations; baffles which the foam strikes at high velocity; liquid or steam jets directed against the foam; and the sudden heating or chilling of coils located in the region where foaming occurs. Serious foam can require an evaporator to be operated at reduced boilup rates to maintain the desired deentrainment space and decontamination factor. If foam is anticipated, the evaporator design should provide reserve capacity, additional deentrainment devices, or foam breakers that will permit the boilup rate to be maintained during foaming.

A.2.4 Volatilization of solute

Volatilization of solute is an important concern in the operation of evaporators with liquid radioactive waste since the design objectives for release of radioactive materials to the environment are low. Several elements found in radwaste, such as iodine and some organics, are volatile to varying degrees. Methods for decreasing the volatility of iodine include adjusting the pH[58,59] and redox potential (e.g., addition of sodium thiosulfate)[60] of the solution or slurry to produce new conditions under which the species is nonvolatile. Iodine exists in aqueous systems in oxidation states from -1 to +7 and forms a number of volatile and nonvolatile inorganic and organic compounds. Ordinarily, iodine present in the -1 oxidation state (iodide) will have a low volatility except at very low pH values or when low-molecular-weight organics are present. Segregation of aqueous from organic waste streams, control of pH values to high basicity, and addition of complexing or other chemical agents to hold the stable iodide state are measures used to improve the decontamination of iodine during evaporation. Volatilization of organics may be a problem if the condensate is to be recycled for use as a heat-transfer medium. These organics can decompose and form deposits on (foul) heating-surface walls and thus cause poor heat-transfer characteristics.

APPENDIX B. DESIGN SPECIFICATIONS FOR EVAPORATORS PROPOSED FOR SOME LWRs NOW UNDER CONSTRUCTION OR PLANNED

Table B-1. Design specifications for evaporators proposed for some pressurized water reactors now under construction or planned[a]

Installation [Capacity]	Number of evaporators	Evaporator type		Materials of construction[d]	Design rating		Entrainment separator	Streams treated	Designer and/or manufacturer	Notes
		Category[b]	Heater[c]		Capacity (gpm)	Pressure (psia)				
Arkansas 2 [2815 MW(t)]	2	FC	E,V,S	Incoloy 825	10	~15	Wire mesh pads in vessel separate from flash chamber	Miscellaneous, chemical, and secondary system wastes	HPD	Evaporator/crystallizer; skid-mounted modules
Bellefonte 1 & 2(*) [3621 MW(t)] ea.		FC	E,H,L	Incoloy 825/ Alloy 20	30	~15	Wire mesh pads in vessel separate from flash chamber	Miscellaneous, chemical, and secondary system wastes	HPD	Evaporator/crystallizer; horizontal heater configuration because of low headroom available
Callaway 1 & 2 (*) [3411 MW (t)] ea.	3	SU	I,H,L	304 SS	15	~15.3	Absorption tower with wire mesh pads	Boric acid and reactor coolant makeup quality wastes	Westinghouse	Feed is to be filtered and degassed
		SU	I,H,L	Incoloy 825	15	~15.3	Absorption tower with wire mesh pads	Miscellaneous and secondary system wastes	Westinghouse	Feed is to be filtered and degassed; unit can be used as backup for boric acid evaporator
		FC	E,V,S	Inconel 625/ Alloy 20	30	~15.3	Wire mesh pads in vessel separate from flash chamber	Chemical and secondary system wastes	HPD	Evaporator/crystallizer; feed is to be filtered but not degassed
McGuire 1 & 2(*) [3411 MW(t)] ea.	2	SU	I,H,L	SS	15	18	Wire mesh and tray with bubble caps	Boric acid	Westinghouse	Components not easily accessible; mounted on two skids
		SU	I,H,L	SS	15	18	Wire mesh and tray with bubble caps	Miscellaneous, chemical and secondary system wastes	Westinghouse	Components not easily accessible; mounted on two skids
Millstone 3 [3411 MW(t)]		FC	E,V,L	Incoloy 825 or Inconel 625	25	30	Distillation trays	Miscellaneous, chemical, and secondary system wastes	Stone & Webster	Components separated into individual shielded cubicles
North Anna 2 [2775 MW(t)]		FC	E,V,L						Stone & Webster	Number of evaporators and size not clear
North Anna 3 & 4 [2631 MW(t)] ea.		FC							Stone & Webster HPD	Number of evaporators and respective suppliers not clear
Palo Verde 1, 2 & 3(*) [3817 MW(t)] ea.	2	FC	E,H,(?)	304 SS	20	21	Wire mesh	Boric acid	Combustion Engineering	Components separated; mounted on two skids
		FC	E,V,L		30	~15	Wire mesh with water sprays	Miscellaneous, chemical, and secondary system wastes	Unitech	Evaporator/crystallizer; components separated though skid-mounted
San Onofre 2 & 3 (*) [3410 MW(t)] ea.	2	SU	I,H,L	304 SS	50		Absorption tower with wire mesh pads	Boric acid	Westinghouse	Mounted on two skids
		SU	I,H,L	304 SS	50		Absorption tower with wire mesh pads	Miscellaneous, chemical, and secondary system wastes	Westinghouse	Mounted on two skids
Sequoyah 1 & 2(*) [3423 MW(t)] ea.	4	SU (2 units)	I,H,L	SS	30	18	Absorption tower with flexitrays	Boric acid and reactor coolant makeup quality wastes	Westinghouse	Original skid-mounted equipment being modified
		SU	I,H,L	SS	2	13	Wire mesh pad and packing rings	Miscellaneous, chemical, and secondary system wastes	Westinghouse	Same as above
		SU	I,H,L	SS	15	18	Absorption tower with wire mesh pads	Miscellaneous, chemical, and secondary system wastes	Westinghouse	Same as above
Shearon Harris 1, 2, 3 & 4 [2775 MW(t)] ea.					15 (2 units)			Reverse osmosis concentrates	HPD	Number of evaporators and respective suppliers not clear
South Texas 1 & 2 [3817 MW(t)] ea.		FC (2 units)	E,V,S	Incoloy 825	30	~15	External entrainment separator	Miscellaneous, chemical, and secondary system wastes	HPD	Evaporator/crystallizer; components in separate cubicles; not skid-mounted
Sterling 1 [3411 MW(t) ea.		FC			30				HPD	Evaporator/crystallizer
Three Mile Island 2(*) [2772 MW(t)]		SU	I,H,S	SS	15	5	Wire mesh	Miscellaneous, chemical, and secondary system wastes	(AMF)-Riley Beaird	Single-skid mounted; components inaccessible

Table B-1 (continued)

Installation [Capacity]	Number of evaporators	Evaporator type		Materials of construction[d]	Design rating		Entrainment separator	Streams treated	Designer and/or manufacturer	Notes
		Category[b]	Heater[c]		Capacity (gpm)	Pressure (psia)				
Tyrone 1 [3411 MW(t)]		FC			30				HPD	Evaporator/crystallizer
Watts Bar 1 & 2(*) [3425 MW(t)] ea.	4	SU (2 units)	I,H,L	SS	30	18	Absorption tower with flexitrays	Boric acid and reactor coolant makeup quality wastes	Westinghouse	Original skid-mounted equipment being modified
		SU	I,H,L	SS	2	18	Wire mesh pad and packing rings	Miscellaneous, chemical, and secondary system wastes	Westinghouse	Same as above
		SU	I,H,L	SS	15	18	Absorption tower with wire mesh pads	Miscellaneous, chemical, and secondary system wastes	Westinghouse	Same as above
WPPSS 3 & 5 [3817 MW(t)] ea.		FC (2 units)	E,V,S	Incoloy 825	30		External entrainment separator	Chemical wastes	HPD	Will serve 4 reactors
		FC	E,V,S	Incoloy 825	20		Same as above	Miscellaneous and secondary system wastes	HPD	Will serve 2 reactors
		WF	E,H,L		~5	~15	Wire mesh with water spray		Artisan	Will serve 2 reactors
Wolf Creek 1 [3411 MW(t)]		FC			30				HPD	Evaporator/crystallizer

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[a] Information for plants marked with an asterisk taken from reply to ORNL survey questionnaires; others taken from responses by NSSS vendors, architect engineers, and evaporator vendors.

[b] FC = forced circulation; NC = natural circulation; SF = spray film; SU = submerged U-tube; WF = wiped film.

[c] E = external; I = internal; H = horizontal; V = vertical; L = long tubes; S = short tubes.

[d] SS = stainless steel.

Table B-2. Design specifications for evaporators proposed for treating chemical and low-purity wastes at some boiling water reactors now under construction or planned[a]

Installation [Capacity]	Number of evaporators	Evaporator type		Materials of construction[d]	Design rating		Entrainment separator	Designer and/or manufacturer	Notes
		Category[b]	Heater[c]		Capacity (gpm)	Pressure (psia)			
Clinton 1 & 2 (*) **[2894 MW(t)] ea.**	3	FC	E,V,S	Incoloy 825 or Alloy 20	30	15-16.5	Wire mesh pads in vessel separate from flash chamber	HPD	Evaporator/crystallizer with solids concentration up to 50% by weight; components are separated
Fermi 2 (*) **[3293 MW(t)]**	1	SU	I,H,S	304L SS	30	~5	Wire mesh	(AMF) - Riley Beaird	Feed will not be degassed, but will be filtered; instrumentation and controls separate from evaporator
Hatch 2 **[2436 MW(t)]**								Unitech	
LaSalle 1 & 2 **[3293 MW(t)] ea.**		FC						Unitech	
Limerick 1 & 2 (*) **[3293 MW(t)] ea.**	2	FC	E,H,S		20	~12	Wire mesh pads and trays	Unitech	Laundry waste may also be treated
Perry 1 & 2 (*) **[2894 MW(t)] ea.**	1	SU	I,H,L	Incoloy 825	30		Wire mesh and bubble-cap trays	Westinghouse	Mounted on two skids
River Bend 1 & 2 **[2894 MW(t)] ea.**	2	FC	E,V,S		35			HPD	Evaporator/crystallizer
WPPSS 2 **[3330 MW(t)]**								Unitech	

[a] Information for plants marked with an asterisk taken from reply to ORNL survey questionnaires; others taken from response by NSSS vendors, architect-engineers, and evaporator vendors.
[b] FC = forced circulation; NC = natural circulation; SF = spray film; SU = submerged U-tube.
[c] E = external; I = internal; H = horizontal; V = vertical; L = long tubes; S = short tubes.
[d] SS = stainless steel.

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:

Architect-engineers

Bechtel Power Corporation
Burns & Roe, Inc.
Ebasco Services, Inc.
Gibbs & Hill, Inc.
Gilbert/Commonwealth Companies
NUS Corporation
Sargent & Lundy
Stone & Webster Engineering Corporation
TERA Corporation
United Engineers & Constructors, Inc.

Evaporator manufacturers and vendors

Artisan Industries
Ecodyne/Unitech Division
HPD Incorporated
LUWA Corporation
Joseph Oat Corporation
Swenson Division/Whiting Corporation

Nuclear-steam-supply system vendors

Babcock and Wilcox Company
Combustion Engineering, Inc.
General Electric Company
Westinghouse Electric Corporation

Utility companies

Arizona Public Service Co.
Arkansas Power & Light Co.
Boston Edison Co.
Carolina Power & Light Co.

Cleveland Electric Illuminating Co.
Commonwealth Edision Co.
Consumers Power Co.
Dairyland Power Cooperative
Detroit Edison Co.
Duke Power Co.
Duquesne Light Co.
Florida Power Corp.
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.)
Maine Yankee Atomic Power Co.
Metropolitan Edison Co.
Niagara Mohawk Power Corp.
Northern States Power Co.
Ohio Edison Co.
Omaha Public Power District
Philadelphia Electric Co.
Portland General Electric Co.
Power Authority of State of New York
Public Service Electric and Gas Co.
Southern California Edison Co.
Tennessee Valley Authority
Toledo Edison Co.
Union Electric Co.
Vermont Yankee Nuclear Power Corp.
Wisconsin Public Service Corp.
Yankee Atomic Electric Co.

Department of Energy (N-Reactor operated by United Nuclear Industries)

Ontario Hydro