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USE OF EVAPORATION FOR THE
TREATMENT OF LIQUIDS IN THE
NUCLEAR INDUSTRY

H. W. Godbee



OAK RIDGE NATIONAL LABORATORY

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USE OF EVAPORATION FOR THE TREATMENT OF LIQUIDS
IN THE NUCLEAR INDUSTRY*

H. W. Godbee

SEPTEMBER 1973

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of Licensing.

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ABSTRACT

A survey of evaporation as applied to radioactive waste solutions was made to evaluate the effectiveness of this unit operation as a treatment method for reducing releases of radioactive effluents to the environment from nuclear power plants. Some nuclear installations have experienced good results with evaporators - achieving decontamination factors of 10^4 to 10^6 from feed to overhead discharge. Others have experienced poor results - achieving decontamination factors of less than 10. Evaporators for radioactive waste vary from simple pots with steam heating pipes coiled inside to elaborate devices with pumps to circulate the feed through outside heaters and compressors for recompressing the vapor to increase its temperature and permit its reuse. Technical data collected include the type of evaporators used; the kinds of ancillary equipment employed such as mist separators, condensers, and preheaters; and the important operating parameters such as vapor velocity, boil-up rate, pressure or vacuum, etc. The results show that a system decontamination factor of 10^3 to 10^4 can be expected for nonvolatile radioactive contaminants treated in single-stage evaporators. Similar decontamination factors can be expected for ruthenium under alkaline, but not acidic and oxidizing, conditions. The decontamination factors for iodine can be expected to be a factor of 10 to 100 lower than those expected for nonvolatile species under alkaline, but not oxidizing or acidic, conditions. Decontamination factors are reduced by a factor of about 10 if organic materials are mixed with aqueous wastes. These values consider that the evaporator is well designed, adequately sized, and operated with reasonable skill.

1.0 SUMMARY AND RECOMMENDATIONS

Operating and design data on evaporators were collected by direct contacts with 30 organizations including suppliers of nuclear steam supply systems, architect-engineers, equipment manufacturers, operators of present and proposed nuclear power stations, as well as selected AEC-operated facilities. The principal emphasis was placed upon data concerning the system decontamination factors (ratios of feed concentrations

to condensate concentration) which were achieved. The report includes decontamination factor (DF) values for different classes of radionuclides based upon their known behavior in boiling solutions, literature data, and operating experience. The basic theoretical and design factors influencing the DF's of evaporators are also presented to facilitate application of the results to the design and evaluation of evaporators for treating liquid radioactive wastes. The results of this survey show that:

- (1) An average system DF of 10^3 to 10^4 can be expected under routine operating conditions for nonvolatile radioactive contaminants treated in evaporators.
- (2) An average system DF of 10^3 to 10^4 can be expected under routine operating conditions for ruthenium in alkaline, but not acidic and oxidizing, solutions.
- (3) An average system DF of 10^2 to 10^3 can be expected under routine operating conditions for iodine in alkaline, but not oxidizing or acidic, solutions.
- (4) Oil, soaps, and detergents mixed with aqueous wastes reduce the DF's by a factor of about 10.
- (5) All of the DF values above consider that the evaporator is well designed, adequately sized, and operated with reasonable skill.
- (6) Higher decontamination factors, 10^5 to 10^6 average system DF's, can be achieved but require simultaneous optimization of all conditions; for example, feed conditions that ensure all solutes are nonvolatile; evaporator design and operating conditions to minimize entrainment; and operator skill and attention to ensure that these conditions are maintained.

Liquid radioactive waste (radwaste) evaporators 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.

The behavior of iodine in liquid radwaste during evaporation is complicated and poorly understood. Laboratory studies to better define

its vapor pressure as a function of pH value, redox potential, and other parameters which determine the physicochemical behavior of iodine are needed. Predicted improved operating conditions should then be confirmed in large-scale evaporator tests.

2.0 BACKGROUND

The purposes of this study were to collect, collate, and report information on the performance of evaporators at nuclear installations, and, in particular, nuclear power plants. Information collected includes quantities of each kind of liquid evaporated, the efficiency with which radionuclides are removed from the stream treated, as well as a comparison of design and operating capacities. The results of this study provide operating data to assist the AEC Directorate of Licensing and the nuclear power industry in their evaluation of the efficiency of evaporators used in liquid radwaste treatment systems at nuclear power plants. In a broader sense, the results are needed to evaluate the role of this unit operation in lowering the discharge of radioactivity in the liquids from any nuclear installation.

In a typical Pressurized Water Reactor (PWR), pressurized light water circulates through the reactor core (heat source) to an external heat sink (steam generator). In the steam generator, where primary and secondary fluids are separated by impervious surfaces to prevent contamination, heat is transferred from the pressurized primary coolant to secondary coolant water to form steam for driving turbines to generate electricity. In a typical Boiling Water Reactor (BWR), light water circulates through the reactor core (heat source) where it boils to form steam that passes to an external heat sink (turbine and condenser). In both reactor types, the primary coolant from the heat sink is purified and recycled to the heat source.

The primary coolant and dissolved impurities are activated by neutron interactions. Materials enter the primary coolant through corrosion of the fuel elements, reactor vessel, piping, and equipment. Activation of these corrosion products adds radioactive nuclides to the primary coolant.

Corrosion inhibitors, such as lithium, are added to the reactor water. A chemical shim, boron, is added to the primary coolant of most PWR's for reactivity control. These chemicals are activated and add radio-nuclides to the primary coolant. Fission products diffuse or leak from fuel elements and add nuclides to the primary coolant. Radioactive materials from all these sources are transported around the system and appear in other parts of the plant through leaks and vents as well as in the effluent streams from processes used to treat the primary coolant. Gaseous and liquid radioactive wastes (radwaste) are processed within the plant to reduce the radioactive nuclides that will be released to the atmosphere and to bodies of water under controlled and monitored conditions in accordance with federal regulations.^{1,2}

The principal methods or unit operations used in the treatment of liquid radwaste at nuclear power plants are filtration, ion exchange, and evaporation as typified for a PWR in Fig. 1 and a BWR in Fig. 2. An example of the volumes of these streams is given in Table 1.

Liquid radwastes in a PWR station are generally segregated into five categories according to their physical and chemical properties as follows:

- a. Clean Waste includes liquids which are primarily controlled releases and leaks from the primary coolant loop and associated equipment. These are liquids of low solids content which are treated in the reactor coolant treatment system.
- b. Dirty or Miscellaneous Waste includes liquids which are collected from the containment building, auxiliary building, and chemical laboratory; regeneration solutions from ion-exchange beds; and solutions of high electrical conductivity and high solids content from miscellaneous sources.
- c. Steam Generator Blowdown Waste is condensate from the steam that is removed (blowdown) periodically to prevent excessive solids buildup.
- d. Turbine Building Drain Waste is leakage from the secondary system that is collected in the turbine building floor sump.

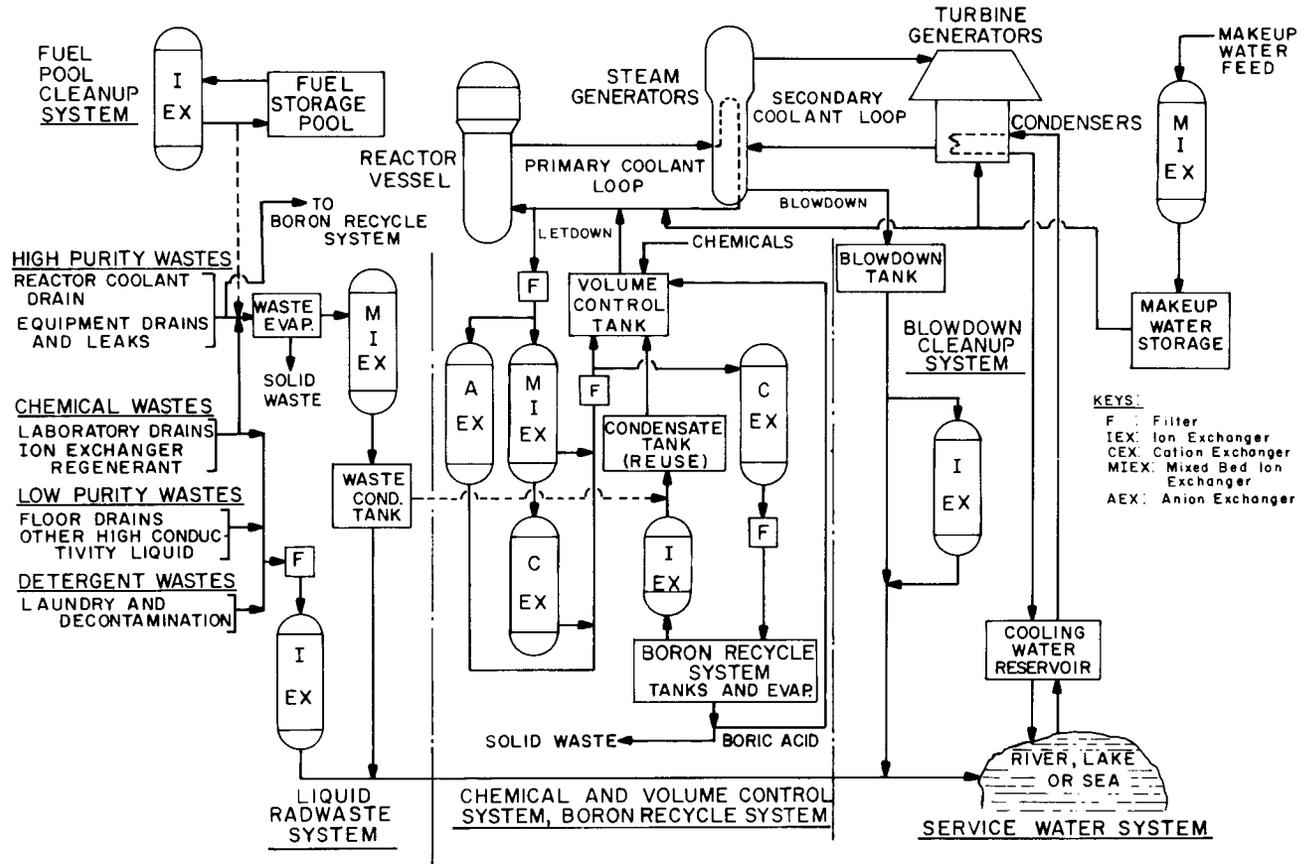


Fig. 1. Typical Liquid Radwaste Treatment System for a Pressurized Water Reactor Nuclear Power Plant. (From ref. 19)

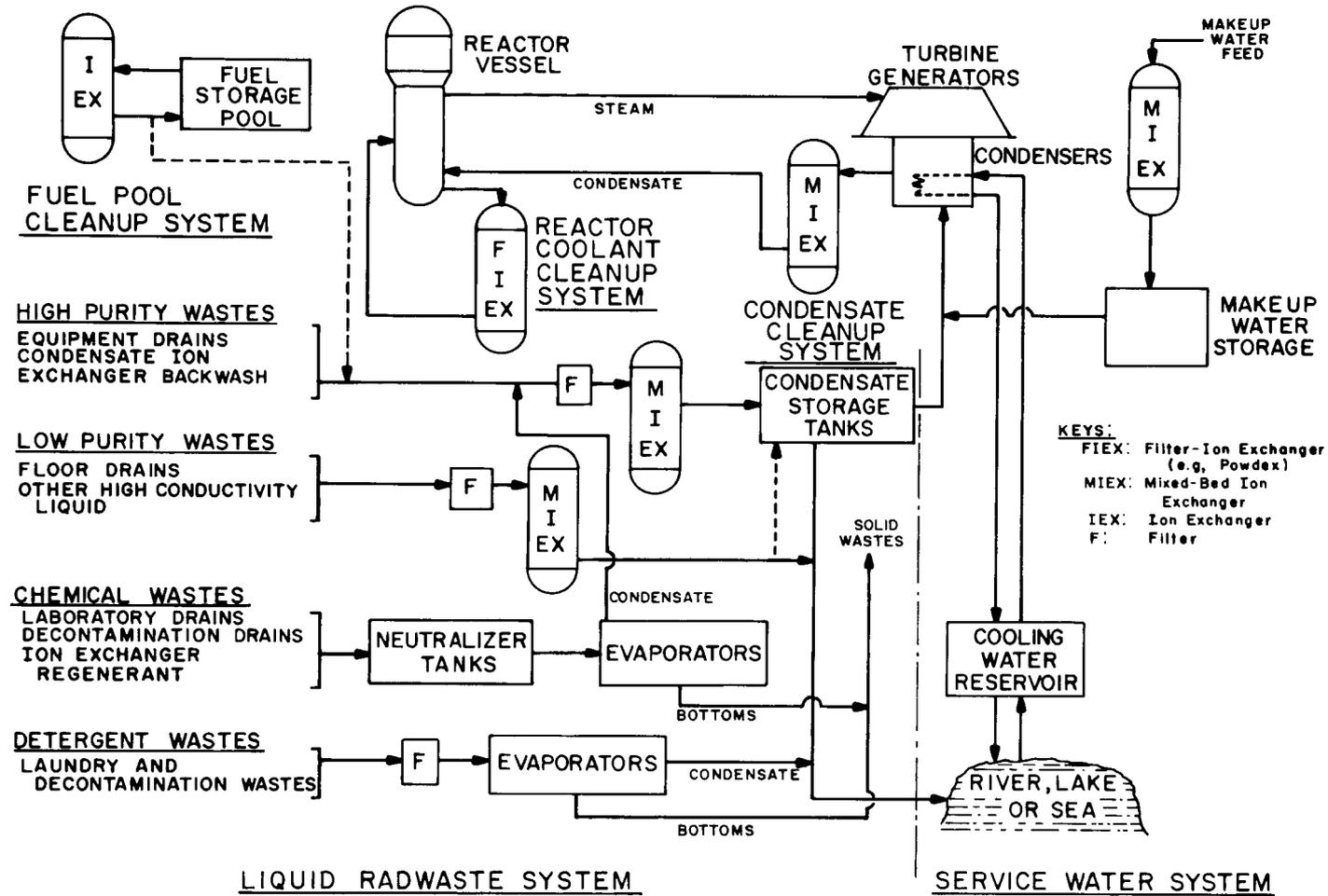


Fig. 2. Typical Liquid Radwaste Treatment System for a Boiling Water Reactor Nuclear Power Plant. (From ref. 19)

Table 1. Average Volumes of Liquid Radwaste for a PWR and a BWR^a

Source	Volume (gpd)	Fraction of Primary Coolant Activity
<u>PWR Liquid Radwaste System</u>		
Containment Building Sump	40	1
Auxiliary Building Floor Drains	200	0.1
Laboratory Drains and Waste Water	400	0.002
Sample Drains ^b	35	1
Turbine Building Floor Drains ^c	7200	Main steam activity
Miscellaneous Sources	700	10 ⁻²
Steam Generator Blowdown	0.06% of main steam flow	0.001
Detergent Waste (laundry, decon- tamination, showers)	450	10 ⁻⁴ μ Ci/ml
<u>BWR Liquid Radwaste System</u>		
Reactor Building Equipment Drain	2000	0.01
Drywell Equipment Drain Sump	5800	1
Radwaste Building Equipment Drain Sump	1000	0.01
Turbine Building Equipment Drains	5700	0.01
Reactor Building Floor Sump	2000	0.01
Drywell Floor Sump	2900	1
Radwaste Building Floor Drain	1000	0.01
Turbine Building Floor Drains	2000	0.01
Laboratory Drains	500	0.02
Condensate Demineralizer Regeneration	1800	Main steam activity
Ultrasonic Resin Cleaning	15,000	0.05
Demineralizer Backwash and Resin Transfer	4200	0.002
Detergent Wastes (laundry, decon- tamination, showers)	450	10 ⁻⁴ μ Ci/ml

^aFrom ref. 3.

^bFifteen gallons per day for continuous purge recycle.

^cFor once-through steam generator systems, equals 3200 gallons per day.

- e. Detergent Waste includes liquids from the laundry, personnel decontamination showers, and equipment decontamination.

The volumes of these wastes for a PWR plant are given in Table 1.

Liquid radwastes in a BWR station are generally segregated into four categories according to their physical and chemical properties as follows:

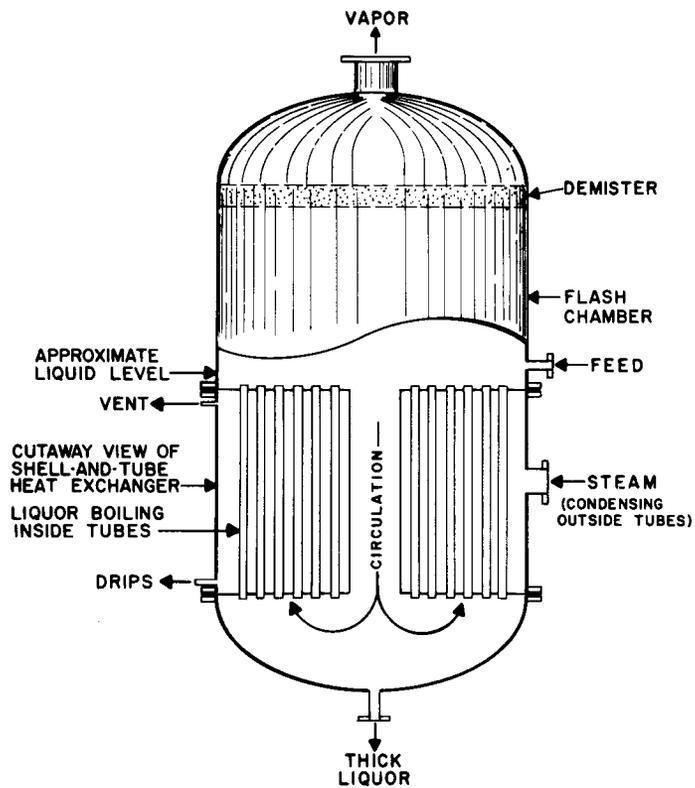
- a. High-Purity Waste includes liquids of low electrical conductivity ($< 50 \mu\text{mho/cm}$) and low solids content, i.e., reactor coolant water that has leaked from the primary reactor system equipment, the drywell floor drain, condensate demineralizer backwash, and other sources of high-quality water.
- b. Low-Purity Waste includes liquids of electrical conductivity in excess of $50 \mu\text{mho/cm}$ and generally less than $100 \mu\text{mho/cm}$; i.e., primarily water from floor drains.
- c. Chemical Waste includes solutions of caustic and sulfuric acid which are used to regenerate ion exchange resins as well as solutions from laboratory drains and equipment decontamination.
- d. Detergent Waste includes liquids from the laundry and personnel decontamination showers.

The volumes of these wastes for a BWR plant are given in Table 1.

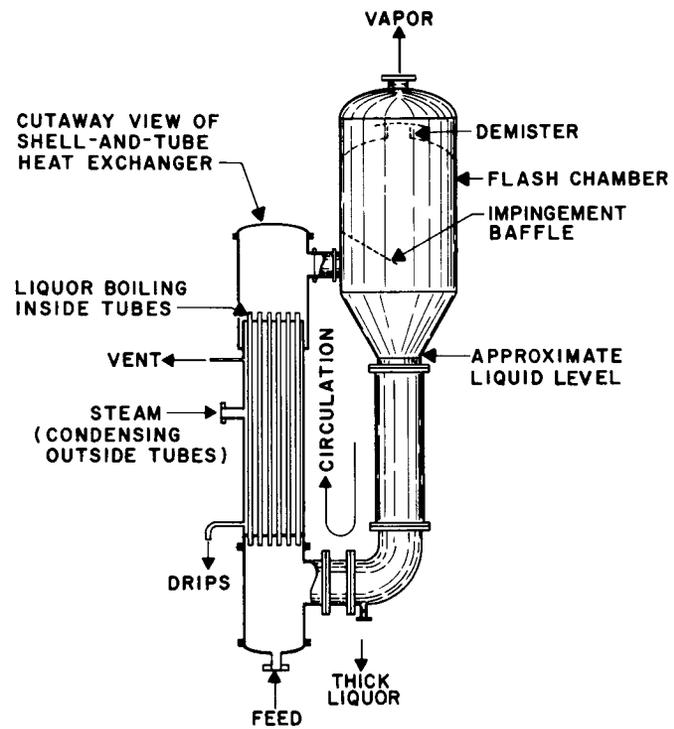
3.0 EVAPORATOR CHARACTERISTICS

Evaporation is the process by which a solution or slurry is concentrated via boiling away the solvent. It is a unit operation that has wide application in the nuclear industry⁴ for reducing waste volumes and for reducing the amount of radioactive nuclides in liquid effluents. Evaporation is usually used for radioactive wastes that require the high degree of separation between volatile and nonvolatile components that it offers or for wastes that are not amenable to treatment by low-temperature operations such as precipitation, filtration, and ion exchange. An evaporator consists basically of a device to transfer heat for boiling the solution or slurry and a device to separate the vapor phase from the liquid phase. The principal elements involved in evaporator design are heat transfer, vapor-liquid separation, volume reduction, and energy utilization. In the design of evaporators for concentrating radioactive liquids, vapor-liquid separation is the most important factor because decontamination of the liquid is the most important objective and heating costs and volume reduction are relatively less important. A small amount of entrainment can contaminate the condensed vapor and reduce the decontamination to unsatisfactorily low levels.

The device in which heat transfer takes place is termed a heating element or calandria. Calandria also describes a type of evaporator that is so common it is often referred to as a standard evaporator (Fig. 3). Many present-day evaporators are equipped with external heaters (Fig. 3). Heaters may be vertical or horizontal, long- or short-tube. Circulation of liquid past the heating surface may be induced by the density variations brought on by boiling (a natural-circulation evaporator) or by mechanical means such as a pump (a forced-circulation evaporator). The device in which vapor-liquid disengaging takes place is called a flash chamber, a vapor head, or sometimes a body. Evaporators used to concentrate radioactive wastes commonly have a large flash chamber so that the flow rate of the vapor is slow, a condition which can induce efficient vapor-liquid separation. Several types of evaporators used and proposed for use at nuclear power plants are shown in Appendix A. These and other types used



CALANDRIA -TYPE EVAPORATOR



LONG-TUBE RECIRCULATION EVAPORATOR

Fig. 3. Typical Evaporators Used in Processing Liquid Radwaste.

at nuclear research laboratories and production sites are reviewed in ref. 4. Evaporator accessories include devices such as entrainment separators, condensers, and vent systems for noncondensable gases. Problems that must be considered in designing or selecting an evaporator include salting, scaling, fouling, corrosion, erosion, and foaming. The advantages and disadvantages of various evaporator types and their applications are treated in more detail in refs. 4-7.

4.0 MODES OF EVAPORATOR 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 continuous operations, feed and product flows are constant and process conditions are constant with time. The operation is at steady state. Three modes of evaporator operation - batch, semicontinuous (or semibatch), and continuous - are defined and described below.

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 very small volume of material is to be concentrated. 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, i.e., 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 (ref. 8) 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 continuous evaporation, startup of the evaporator is carried out as for the semicontinuous operation described above. After the desired concentration of thick liquor has been reached, a thick liquor stream is withdrawn continuously from the evaporator. Pressures, temperatures, concentrations, as well as feed, condensate, and thick liquor flow rates are held constant. This mode of operation is used at nuclear installations and is widely used in the process chemicals industry. Flow-sheets illustrating a placement of evaporators used to treat liquid radwastes at nuclear power plants are given in Figs. 1 and 2.

5.0 DEFINITION OF DECONTAMINATION FACTORS

The effectiveness of unit operations such as demineralization (ion exchange), filtration, centrifugation, and evaporation for reducing the radioactivity in effluent streams from nuclear installations is usually expressed in terms of the decontamination factor (DF) for each isotope of concern and gross activity. The instantaneous decontamination factor across the evaporator system, $(DF)_{si}$, often called the process DF, is defined as the ratio of the feed concentration at any time to the condensate concentration at that time. The average system DF, $(\overline{DF})_s$, is the ratio of the feed concentration to the average condensate concentration. Evaporator manufacturers frequently use an equipment or evaporator DF, $(DF)_e$, which is defined as the ratio of the thick liquor concentration to the condensate concentration. The interrelationships between $(DF)_s$'s and $(DF)_e$'s for the three modes of evaporator operation defined in Sect. 4 are derived in Appendix B.

As ref. 8 points out, sampling and accurately analyzing the thick liquor from an evaporator treating liquids containing radioactive materials are difficult or nearly impossible. Evaporator DF's are more readily

determined from the measured system DF's and the appropriate concentration factors (Appendix B). Not only is the system DF more easily and accurately determined, it is directly applicable to defining the reduction in the amount of radioactive materials released to the environment. This is the value needed for determining the environmental impact.

6.0 FACTORS INFLUENCING THE DF'S 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, ruthenium, 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 - 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.

6.1 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 distribution of the droplets. 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 formed⁹⁻¹¹ 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 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 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, i.e., sharply varying vacuum.

At higher boilup rates, entrainment increases and thus the DF generally decreases with increasing boilup rate as shown by the empirical correlation¹² for DF's given in Appendix C (Fig. C-1). These results could imply that at lower boilup rates the decontamination factor would be higher. However, at very low boilup rates the decontamination factor decreases with decreasing boilup rate.^{4,11,13,14} Smaller vapor bubbles produced by gentle boiling lead to the production of smaller droplets which 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 velocity¹¹ of around 20 to 40 lb ft⁻² hr⁻¹, where the velocity is calculated at the largest horizontal cross-sectional area for vapor flow. 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 DF's 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 as illustrated by the data from ref. 11 presented in Appendix C (Fig. C-2). The overall decontamination factor for the

evaporator plus deentrainment devices may differ widely from the DF for the evaporator alone.¹¹

The importance of deentrainment devices that augment the evaporator DF and of proper vacuum control is illustrated by consideration of an evaporator installed at Ginna Nuclear Power Plant (Fig. 4). As determined from operating experience,¹⁵ the values of the system DF for the evaporator as originally installed were 10^2 or less. Design specifications called for a system DF of 10^5 at a volume reduction factor of 20. When the reactor was shut down for refueling in 1971, the evaporator system was modified and recent operating results¹⁶ show system DF's from 10^3 to mid 10^5 . These modifications¹⁷ included: (1) installation of steam jet pumps in place of the original mechanical vacuum pumps to improve vacuum control and (2) alterations to the evaporator internals that consist of additional mesh separators, removal of downcomers, relocation of the reflux line, and surrounding the heater bundle with a baffle assembly (Fig. 4). Similar modifications have been or are being made to evaporators of this type at other nuclear power plants (Point Beach, H. B. Robinson Unit 2, and Turkey Point).

6.2 Splashover

Splashover consists of the carryover 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 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.

6.3 Foam

Foam implies 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

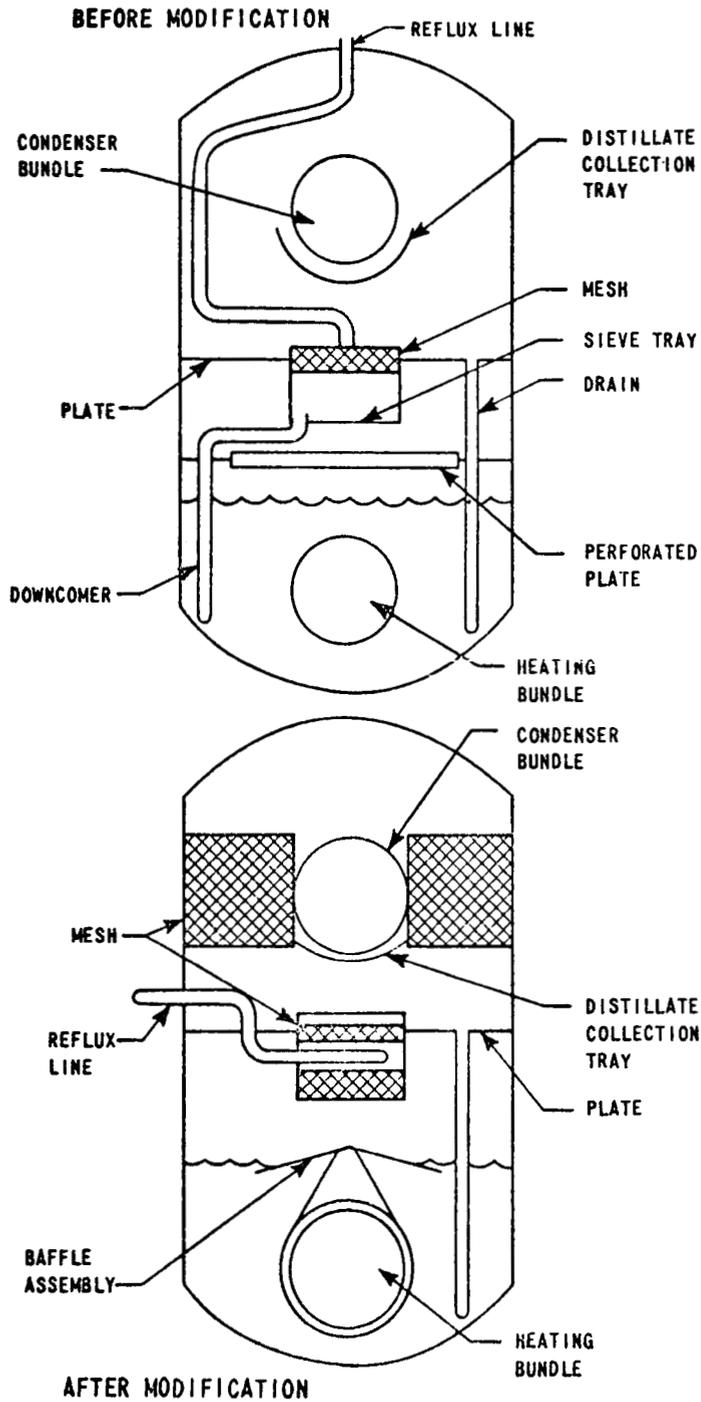


Fig. 4. Modifications to the AMF Ray-Di-Pak Evaporator. (From ref. 17)

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 cause 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.

6.4 Volatilization of Solute

Volatilization of solute, though usually not of concern in the design of evaporators, 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 ruthenium and iodine, as well as some organics are volatile to varying degrees. Methods for decreasing the volatility of ruthenium and iodine include adjusting the pH and redox potential of the solution or slurry to produce new conditions under which the species is nonvolatile. Ruthenium is generally not volatile during evaporation of nonoxidizing alkaline solutions but is sometimes slightly volatile during evaporation of oxidizing alkaline solutions. However, volatile ruthenium tetroxide is usually evolved from boiling solutions of oxidizing acids in amounts ranging from several percent to several tens of percent. The decontamination factor for ruthenium during evaporation of such solutions is improved by addition of caustic to give high pH values and addition of reducing agents such as sugar, formaldehyde, or formic acid. 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.

Data from Oak Ridge National Laboratory (ORNL) on the decontamination factors obtained during the evaporation of a simulated intermediate-level radioactive waste (pH of about 11) and a simulated borate waste (pH of about 13) with selected organic and inorganic additives are given in Appendix D. The composition of the simulated wastes (0.2 to 0.4 $\mu\text{Ci/ml}$) and a schematic of the small-scale equipment used in these studies are also given in Appendix D. The average system decontamination factors are low 10^4 for cesium, sodium, and strontium; in the range of mid 10^3 to low 10^4 for ruthenium; and in the range of mid 10 to low 10^4 for iodine. Representative results are shown in Figs. 5 and 6. In a qualitative sense, for the alkaline solutions studied, cesium, sodium, and strontium represent nonvolatile solutes; ruthenium a moderately volatile to nonvolatile solute; and iodine a volatile to nonvolatile solute depending upon the chemistry (the ratio of iodide to elemental iodine and the ratio of radioactive to nonradioactive iodine in organic compounds) of the solution. These results for cesium, sodium, and strontium in a small-scale calandria evaporator compare favorably with the results¹⁸ for sodium in a pilot-plant-scale forced-circulation evaporator and with the results^{4,11} for lithium in a small-scale and pilot-plant-scale vertical-tube evaporator.

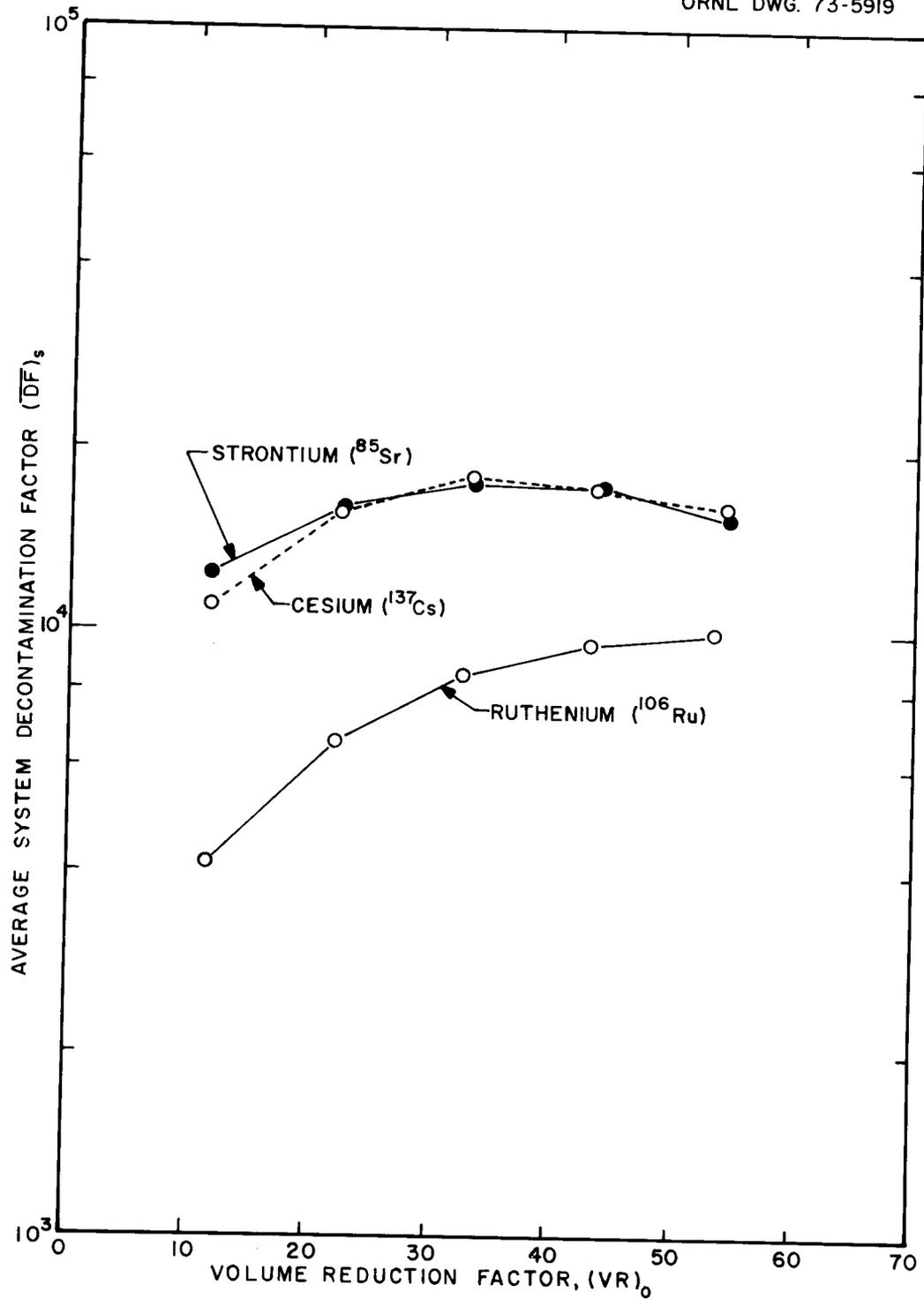


Fig. 5. Average System Decontamination Factors for Cesium, Ruthenium, and Strontium During Evaporation of Simulated ORNL Intermediate-Level Radioactive Waste. (From Appendix D)

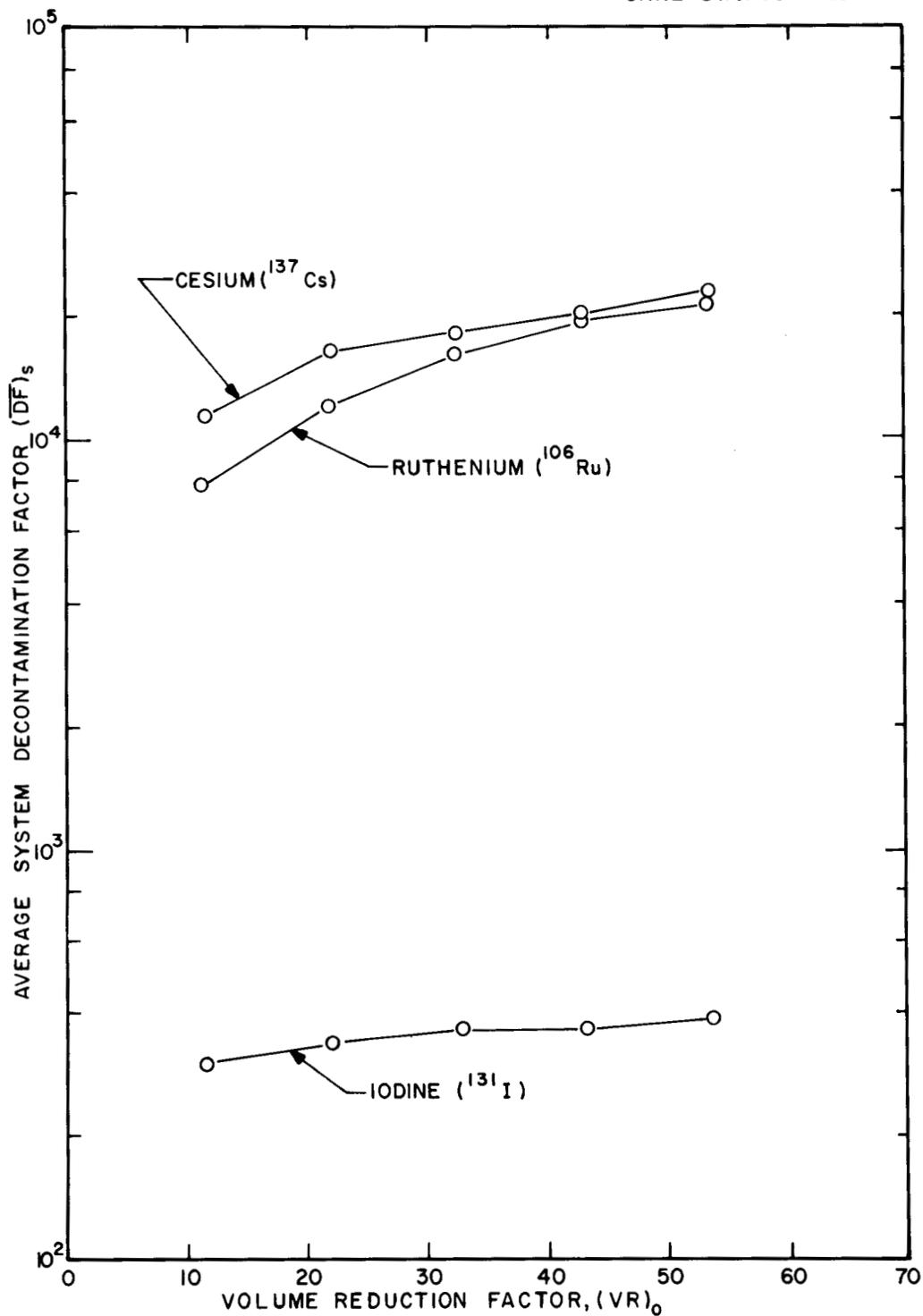


Fig. 6. Average System Decontamination Factors for Cesium, Ruthenium, and Iodine During Evaporation of a Simulated Radioactive Borate Waste. (From Appendix D)

7.0 INDUSTRIAL APPLICATION OF EVAPORATORS

Thirty organizations were contacted to obtain design and operating data on the performance of evaporators. These organizations included 14 utility companies, 7 evaporator manufacturers, 4 suppliers of nuclear steam supply systems, 2 architect-engineering firms, and 3 AEC operated facilities. The data obtained from the 18 organizations that responded to the inquiries are summarized in Tables 2-5, Figs. 7-9, Appendices E-H, and are discussed in the following sections. A compilation of design specifications for evaporators at nuclear power plants obtained from responses to the inquiries and gleaned from AEC dockets during the survey is given in Appendix I. A typical arrangement for a waste evaporator and associated equipment at a nuclear power plant is shown in Fig. 7.

Much of the information received contained little detail on feed compositions, operating conditions, decontamination factors, problems and the actions taken to correct them. A supplemental survey and compilation will prove valuable as the nuclear industry gains more experience and operating information. A similar survey on the application of ion exchange in the nuclear industry is given in ref. 19.

7.1 Vendors of Nuclear Steam Supply Systems and Architect-Engineers

General Electric Company (GE) assumes an average system decontamination factor, $(\overline{DF})_s$, of 10^3 with variations from 10^2 to 10^4 . GE also specifies an upper limit of 1 to 2 ppm solids in the condensate. A $(\overline{DF})_s$ of 10^2 represents abnormal operations such as foaming or splashover. In design verification tests with simulated waste containing fission product salts and sodium sulfate, but no phosphates or detergents, GE has routinely achieved a $(\overline{DF})_s$ of 10^4 . No specific isotopes were reported for these tests. In GE-designed plants, the condensate is processed through a filter and an ion exchange column to obtain additional decontamination. Early plants have a Swenson long vertical-tube evaporator with external heater and natural circulation (cf. Fig. A-5 in Appendix A). Later plants have a similar type manufactured by Aqua-Chem. Currently, GE is using a Unitech

Table 2. Typical Design Specifications for Evaporators Used at Nuclear Power Plants

Installation [Capacity] Reactor Type	Waste Stream Treated ^a	Evaporator Type				Circulation	Manufacturer	Number of Units	Design Rated		Entrainment Separators
		Tubes		Natural	Forced				Capacity (gal/min)	DF for Gross Activity	
		Internal	External								
Dresden 2 & 3 [2527 MW(t)] ea. BWR	Chemical		X		X	X	Aqua-chem ^b	2 ^c	25	1×10^3 (\overline{DF}) _s	Baffle and wire mesh
Ginna [1300 MW(t)] PWR	Dirty	X		X		X ^d	AMF ^e	1	2	1×10^6 (\overline{DF}) _e	Splash plate and wire mesh
	Clean	X		X		X ^d	AMF	1	12.5	1×10^6 (\overline{DF}) _e	Perforated plate, sieve tray, and wire mesh
Humboldt Bay [240 MW(t)] BWR	Chemical	X			X	X	Thermovac ^f	1 ^g	1	Unknown	None
	Low Purity	X			X	X	Thermovac	1 ^g	1	Unknown	None
Limerick 1 & 2 [3293 MW(t)] ea. BWR	Chemical		X	X		X	Unitech ^h	2	18.5	1×10^4 to 1×10^5 (\overline{DF}) _e	Trays and wire mesh
Nine Mile Point [1850 MW(t)] BWR	Chemical ⁱ	X			X	X	Swenson ^j		10	Unknown	Wire mesh
Oconee 1 [2452 MW(t)] 2 & 3 [2584 MW(t)] PWR	Dirty	X		X		X ^k	Aqua-chem	1 ^l	7.5	1×10^5 (\overline{DF}) _s	Wire mesh with spray nozzles
	Clean	X		X		X ^k	Aqua-chem	1 ^l	7.5	1×10^5 (\overline{DF}) _s	Wire mesh with spray nozzles
Point Beach 1 & 2 [1518 MW(t)] ea. PWR	Dirty ^m	X		X		X ^d	AMF	1	2	1×10^6 (\overline{DF}) _e	Perforated plate, sieve tray, and wire mesh
	Clean	X		X		X ^d	AMF	1	12.5	1×10^6 (\overline{DF}) _e	Perforated plate, sieve tray, and wire mesh
Point Beach 1 & 2 [1518 MW(t)] ea. PWR	Dirty		X		X	X	Stone & Webster ⁿ	1	35	1×10^4 (\overline{DF}) _s	Distillation trays
Sequoyah 1 & 2 [3423 MW(t)] ea. PWR	Dirty	X		X		X ^k	WHED ^o	1	5	1×10^5 (\overline{DF}) _e	Packing rings and wire mesh
	Clean	X		X		X ^k	WHED	2	30	1×10^5 (\overline{DF}) _e	Trays in absorption tower
Zion 1 & 2 [3391 MW(t)] ea. PWR	Dirty	X		X		X ^k	Aqua-chem	1	15	1×10^6 (\overline{DF}) _e	Wire mesh with spray nozzles
	Clean	X		X		X ^k	WHED	1	20	1×10^6 (\overline{DF}) _e	Absorption tower

^aSee Figs. 1 and 2 and Table 1 for sources of waste.

^bAqua-Chem, Inc., Milwaukee, Wisconsin.

^cOne evaporator in use; one presently in reserve.

^dWaste is circulated between evaporator and feed tank.

^eAmerican Machine & Foundry Company, York, Pennsylvania.

^fThermovac Industries Corp., Copiague, New York.

^gThe same unit is used for both wastes.

^hThe Unitech Company, Union, New Jersey.

ⁱA new 20-gpm forced-circulation type is planned.

^jSwenson Evaporator Company, Harvey, Illinois.

^kFeed sprays down onto heater tubes.

^lOne dirty-waste and one clean-waste evaporator for the 3 reactors.

^mNew dirty-waste evaporator being installed at Point Beach.

ⁿStone and Webster Engineering Corporation, Boston, Massachusetts.

^oWestinghouse Heat Transfer Division, Monroeville, Pennsylvania.

Table 3. Performance of Evaporators Used at Nuclear Power Plants^a

Installation [Capacity] Reactor Type	Waste Stream ^b Treated	Evaporator Capacity (gal/min)				Time Operated (%)		Pressure (psia)	Anti-foam Agent	Volume Reduction (feed/thick liquor)	Condensate Treatment	Comments by Utility
		Design	Max	Min	Avg	Normal	Abnormal					
Dresden 2 & 3 [2527 MW(t)] ea. BWR	Chemical	25	~21	~20	20	80	-	45	Dow B	8	Filter and ion exchange (mixed bed)	Performance below de- sign.
Ginna [1300 MW(t)] PWR	Dirty ^c	2	2	2	2	10-25	~100	4	Dow H-10	10-70 (20 avg)	Ion exchange (mixed bed)	Performance below de- sign.
Humboldt Bay [240 MW(t)] BWR	Chemical	1	1	0.2	0.5	30 ^d	-	15	Yes	25	Filter	Performance below de- sign.
	Low Purity	1	1	0.2	0.5	30 ^d	-	15	Yes	1000	Filter	Performance below de- sign.
Nine Mile Point [1850 MW(t)] BWR	Chemical	10	-	-	3	36	-	15	No	50-100	Ion exchange (mixed bed)	Performance slightly below design.
Point Beach 1 & 2 [1518 MW(t)] ea. PWR	Dirty ^e	2	1	1	1	~100	-	2	Dow H-10	24-40	Filter (mixed bed ion exchange being added)	Performance below de- sign. Modifications being made. ^f
	Clean	12.5	12.5	12.5	12.5	10-30	-	6-7	No	~12	Ion exchange (anion) and filter	Performance at design.

^aEvaporators operated in semicontinuous mode as defined in Sect. 4.

^bSee Figs. 1 and 2 and Table 1 for sources of waste.

^cAMF 2-gpm evaporator with modifications described in ref. 17.

^dSame evaporator used for chemical and high-purity waste; time is for evaporating both wastes.

^eAMF 2-gpm evaporator without modifications described in ref. 17.

^fSee ref. 17 for modifications being made.

Table 4. Performance Data^a for the Oyster Creek Nuclear Generating Station Waste Evaporator Treating Condensate-Demineralizer Regeneration Solution

Nuclide	Half-Life	Concentration ($\mu\text{Ci/ml}$)		Average System DF ^b
		Feed	Condensate	
⁶⁰ Co	5.26 y	7.4×10^{-3}	$<1.3 \times 10^{-8}$	$>5.7 \times 10^5$
¹³¹ I	8.1 d	4.6×10^{-3}	$<2 \times 10^{-8}$	$>2.3 \times 10^3$
¹⁴⁰ Ba	12.8 d	2.0×10^{-3}	$<1 \times 10^{-6}$	$>2 \times 10^3$
⁵⁴ Mn	303 d	1.3×10^{-3}	$<1.5 \times 10^{-8}$	$>8.7 \times 10^4$
¹³⁷ Cs	30 y	9.0×10^{-4}	1.8×10^{-8}	5×10^4
⁵¹ Cr	27.8 d	7.1×10^{-4}	$<6 \times 10^{-7}$	$>1.2 \times 10^3$
⁵⁸ Co	71.3 d	5.9×10^{-4}	-	-
¹³⁴ Cs	2.05 y	4.5×10^{-4}	$<9 \times 10^{-9}$	$>5 \times 10^4$
⁸⁹ Sr	51 d	3.8×10^{-4}	$<1.5 \times 10^{-8}$	$>2.5 \times 10^4$
¹⁴¹ Ce	33 d	9.0×10^{-5}	$<1 \times 10^{-7}$	$>9 \times 10^2$
⁹⁰ Sr	28 y	2.3×10^{-5}	$<2.2 \times 10^{-8}$	$>1 \times 10^3$

^aFrom ref. 20.

^bAverage system decontamination factor, $(\overline{\text{DF}})_s$, defined as the feed concentration divided by the average condensate concentration.

Table 5. Performance of Evaporators Used at AEC-Operated Facilities

Installation	Waste Stream Treated	Evaporator Capacity (gal/min)				Time Operated (%)	Pressure (psia)	Anti-foam Agent	Mode of Operation	Volume Reduction (feed/thick liquor)	Condensate Treatment	Comments by Installation
		Design	Max.	Min.	Avg.							
NRTS: ^a												
TAN ^b	Chemical (Slightly basic)	1.7	1	0.8	0.9	4-6	10	Dow DB-31	Semicontinuous	10	Discharge or recycle to evaporator	Performance is below that originally achieved
ANL ^c	Chemical (slightly basic)	4.2			0.4	0-20	~15	No	Semicontinuous	50	Discharge or recycle to evaporator	Performance below design. System being modified.
ICPP ^d	Chemical (Acidic and basic)	12.5	12.5		8	30	12	No	Semicontinuous	30	Ion exchange (cation)	Performance at design level. Some scaling of tubes.
ORNL ^e	Chemical (Basic)	10	7	4	5	~100	~15	Dow A	Semicontinuous	25-75; 35 avg.	Ion exchange and modified lime-soda water treatment	Performance below design specifications on rate and DF
SRP: ^f												
GPE ^g	Chemical (Basic, NaNO ₃ + NaOH)	12	12		10	30	3	No	Semicontinuous	50	None	Performance at design specifications.
CE ^h	Chemical (Acidic, 1 M HNO ₃ + traces)	40	40	8	28	30	~15	No	Continuous	30	Fractionated to recover HNO ₃	Performance at design specifications. Design capacity not required.
PTE ⁱ	Chemical [Acidic, 1 M HNO ₃ + 1.2 M Al(NO ₃) ₃]	8	8	3	6	80	~15	No	Semicontinuous	2-35	Fractionated to recover HNO ₃	Performance at design specifications

^aNational Reactor Testing Station (NRTS), Idaho.

^bTest Area North (TAN); see Appendix F for more detail on waste and evaporator.

^cArgonne National Laboratory (ANL) West - operator of the EBR-II site at the National Reactor Testing Station, Idaho. The evaporator referred to is of the type shown in Fig. A-5 of Appendix A. The evaporator system at ANL is presently undergoing extensive modifications; but, no operating data on the performance of these modifications are yet available.

^dIdaho Chemical Processing Plant (ICPP); see Appendix G for more detail on waste and evaporator.

^eOak Ridge National Laboratory (ORNL); see Appendix H for more detail on waste and evaporator.

^fSavannah River Plant (SRP), Aiken, South Carolina.

^gGeneral Purpose Evaporators (GPE) of the type shown in Fig. A-6 of Appendix A. Vapors pass through four wet bubble-cap trays.

^hContinuous Evaporators (CE) of the type shown in Fig. A-5 of Appendix A. Vapors pass through three bubble-cap trays (bottom dry, middle wet, top dry).

ⁱPot Type Evaporators (PTE) of the type shown in Fig. A-1 of Appendix A with steam coils instead of tube-and-shell heat exchanger. Vapors pass through three wet bubble-cap trays.

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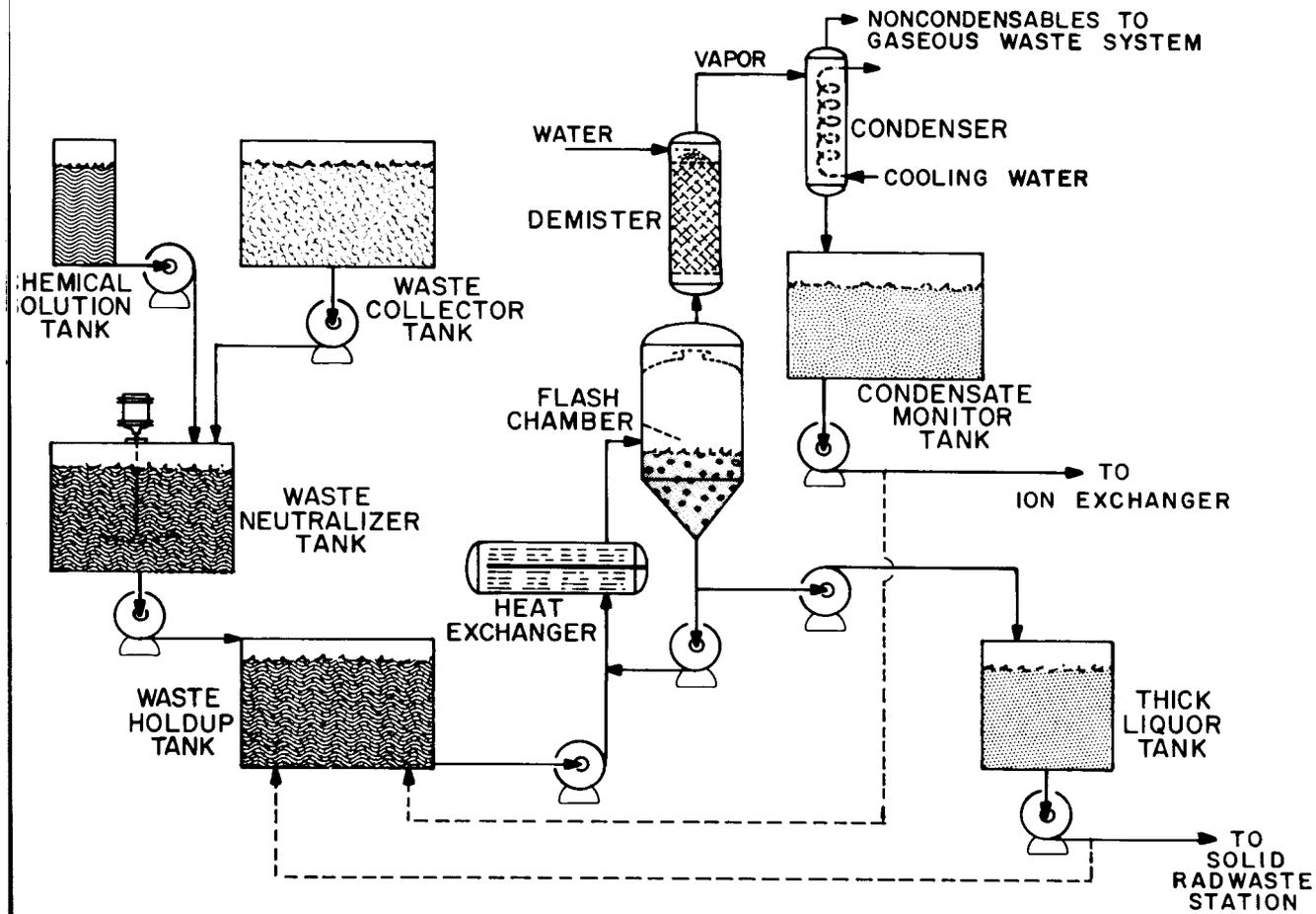
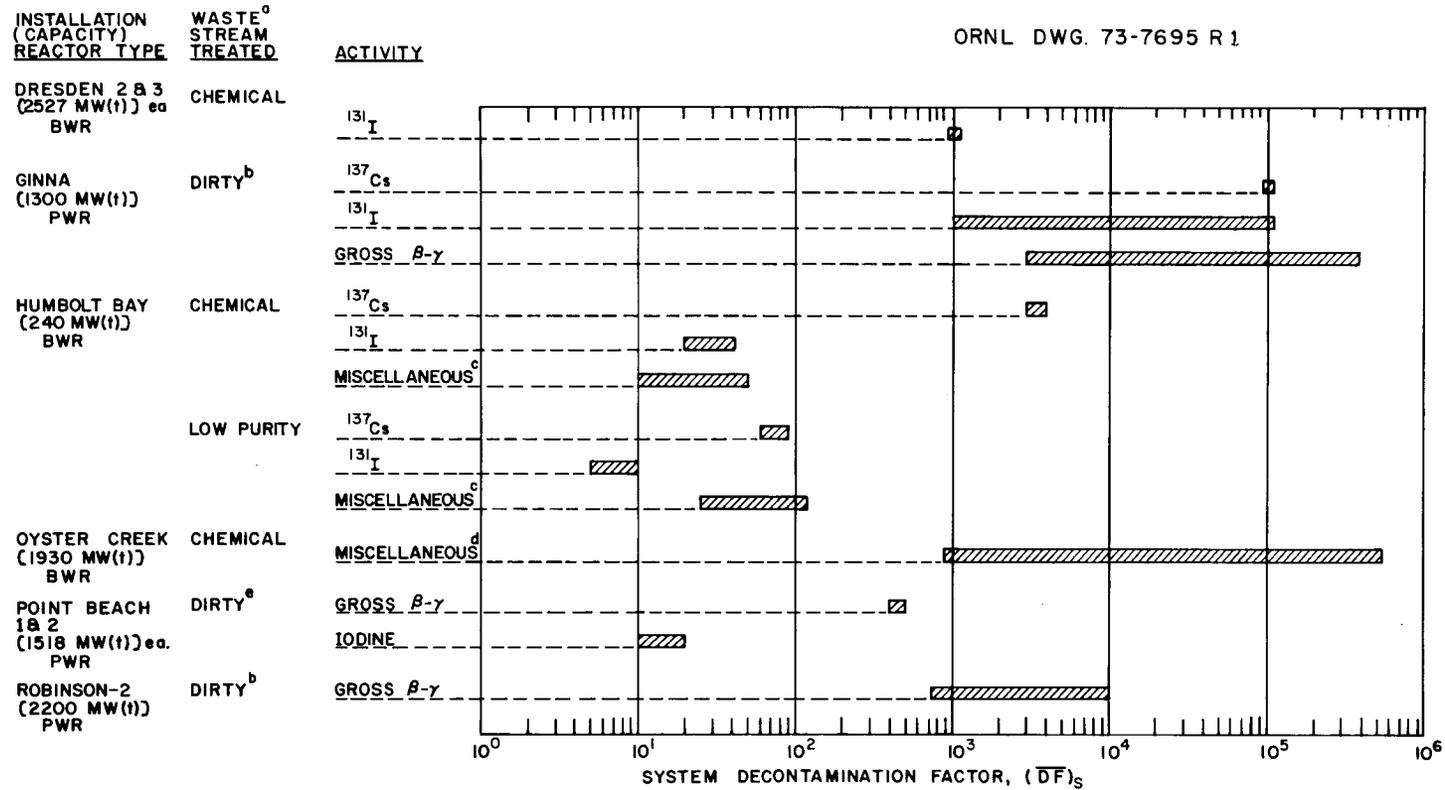
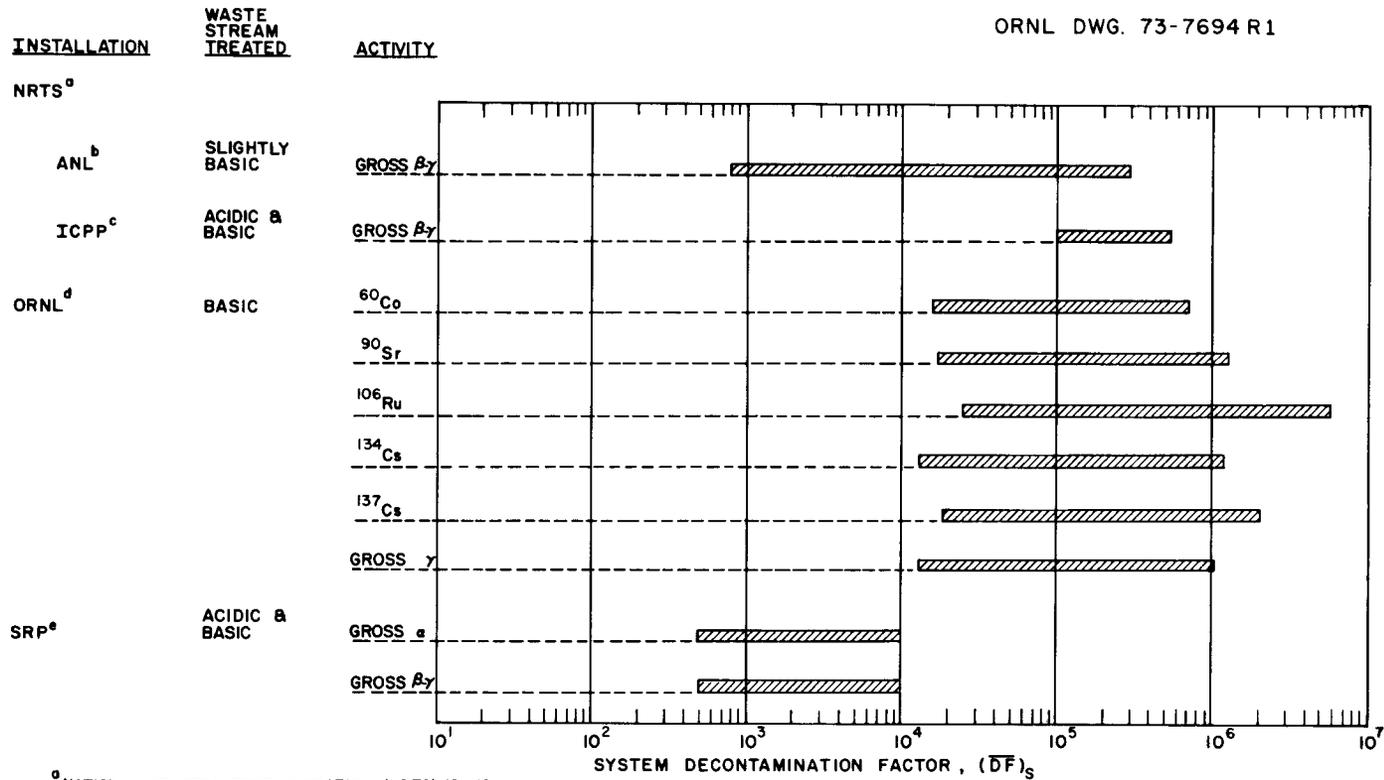


Fig. 7. Typical Arrangement of Waste Evaporator and Associated Equipment at a Nuclear Power Plant.



^a SEE Figs. 1 AND 2 AND TABLE 1 FOR SOURCES OF WASTE.
^b AMF 2-GPM EVAPORATOR WITH MODIFICATIONS DESCRIBED IN REF. 17
^c INCLUDES ⁵⁴Mn, ⁶⁰Co, ⁶⁵Zn, AND ¹⁴⁰La
^d SEE TABLE 4 FOR LIST OF ISOTOPES.
^e AMF 2-GPM EVAPORATOR WITHOUT MODIFICATIONS DESCRIBED IN REF. 17

Fig. 8. Comparison of System Decontamination Factors from Several Operating Nuclear Power Plants.



^a NATIONAL REACTOR TESTING STATION (NRTS), IDAHO.
^b ARGONNE NATIONAL LABORATORY (ANL) WEST, AT THE NRTS, IDAHO.
^c IDAHO CHEMICAL PROCESSING PLANT (ICPP) AT THE NRTS, IDAHO. SEE APPENDIX G.
^d OAK RIDGE NATIONAL LABORATORY (ORNL), OAK RIDGE, TENNESSEE, SEE APPENDIX H.
^e SAVANNAH RIVER PLANT (SRP), AIKEN, SOUTH CAROLINA.

Fig. 9. Comparison of System Decontamination Factors from Several AEC-Operated Facilities.

falling-film evaporator with forced circulation (cf. Fig. A-9 in Appendix A). GE believes this type is better for handling sludges. All the units furnished by GE have several inches of wire mesh in the flash chamber for demisting. The capacities of the evaporators vary from 10 to 25 gal/min and they are operated in a semi-continuous mode.

Westinghouse Electric Corporation assumes that an average equipment decontamination factor, $(\overline{DF})_e$, of 10^5 (including iodine) can be obtained with a properly designed and operated evaporator. The capacities of evaporators at Westinghouse PWR's range up to 30 gal/min. The same size is used in the chemical and volume control system (CVCS) and the radwaste treatment system. Westinghouse is now designing and testing evaporators for use at nuclear power plants. One design is based on the horizontal-tube evaporator with U-bend tubes shown in Fig. A-3 (Appendix A) with the feed sprayed down onto the tubes. Another appears to be similar to the modified AMF 2-gpm unit (Fig. 4) with further modifications of the internals, steam in place of hot water heating, and an external condenser instead of the internal one. Vapors from the evaporators pass through absorption columns containing trays or packing rings and wire mesh.

Bechtel Corporation assumes a $(\overline{DF})_e$ of 10^3 but has achieved 10^8 in tests with radioactive sodium tracer. Bechtel states that recycle of organic materials from laboratory or decontamination wastes through an evaporator is undesirable since volatile organic material, such as hexone (methylisobutyl ketone), pass into the purified water. When recycled to the reactor, these organics could decompose and deposit on hot surfaces, such as fuel elements, and seriously affect operations. Bechtel reports that dirty or miscellaneous waste (such as decontamination solutions, demineralizer regenerant solutions, and laboratory wastes) is the largest source of radioactive materials which must be evaporated, solidified, and shipped off-site. These solutions [18,000 to 20,000 gal/day at a 1000-MW(e) BWR plant] contain about 1% Na_2SO_4 and are concentrated by evaporation to 20-25% Na_2SO_4 .

Stone and Webster (S&W) assumes a $(\overline{DF})_s$, evaluated at the maximum feed-to-thick liquor ratio, of 10^4 . S&W believes that, based on their

tests and experience, this is a reasonable value for an evaporator designed specifically to reduce entrainment and leaves some margin for upsets and differing volatilities of isotopes such as iodine under low pH, oxidizing conditions, etc. In recent evaporators, S&W has modified the design of the vapor-liquid separator section to limit entrainment as well as volatilization of boron and iodine. Trays with a design DF of 8 per tray are used above and below the feed point for this purpose. Five to eight trays are used. The S&W evaporator designed for use at nuclear power plants has a vertical, external, shell-and-tube heat exchanger. To reduce or eliminate the deposition of solids on heating surfaces, no vaporization occurs within the exchanger. This is accomplished by forced circulation in conjunction with a restriction device in the heat exchanger outlet line. An evaporator incorporating these features is depicted in Fig. A-10 (Appendix A). The largest unit designed by S&W thus far has a capacity of 35 gal/min.

7.2 Utility Companies

Typical design specifications for evaporators used at nuclear power plants are presented in Table 2 and typical operating results in Table 3. Examples of evaporator types used and proposed for use in the nuclear power industry are shown in Appendix A. The established single-stage chemical evaporators (depicted in Figs. A-1 to A-6 of Appendix A) and variations thereon are widely used at nuclear power plants as shown by the listing in Appendix I. Pilgrim-1, Indian Point-1, and Shippingport report having the vapor-compression type (cf. Fig. A-7 in Appendix A). Connecticut Yankee's Haddam Neck plant has a unit that could be considered a double-effect evaporator (cf. Fig. A-8 in Appendix A), but it is not operated as such. One way the unit is operated at Haddam Neck is with the condensate from the first evaporator being condensed in the heat exchanger of the second and this condensate being used as feed to the second evaporator. Another way is as two evaporators in parallel. The FitzPatrick radwaste system specifies a turbulent-film evaporator (cf. Fig. A-11) to further concentrate the thick liquor (~25 wt % solids) from the waste evaporator to a product containing 60 to 70 wt % solids. Other

plants, Humboldt Bay and Indian Point, are reported to be considering this type evaporator for further concentration of wastes.

Essentially all plants have experienced some difficulties with organic materials and foaming. These problems have generally been dealt with by careful segregation of aqueous and organic wastes and by use of anti-foam agents. Results with the antifoam agents used (the silicone preparations) seem to be about equally split between good results and no effect. Several plants - among them, Ginna, Point Beach, and H. B. Robinson Unit No. 2 - were unable to achieve the design levels of boil-off rate, vacuum control, and decontamination with their evaporators as originally installed. The modifications to these evaporators to improve performance are discussed in Sect. 6.1. Most evaporators have been required to process more waste than predicted by design estimates. This is reflected in the fact that when evaporators are replaced, the replacement unit usually has a higher rate than the original unit. For example, the new unit at Point Beach will be 35 gpm vs 2 gpm and at Nine Mile Point 20 gpm vs 10 gpm.

Corrosion is a principal concern with evaporators. Dresden 2 reported that the original evaporator failed due to acid attack (sulfuric acid from the incomplete neutralization of demineralizer regenerant solutions). The replacement unit is made of 316L stainless steel while the original was made of 304L and 308. The tubes of heat exchangers sometimes plug with solids. Some tube plugging has occurred in the evaporator at Oyster Creek and caused reduced boil-off rates. Evaporators that do not depend on boiling to induce circulation (i.e., forced-circulation evaporators) or evaporators with low vapor release in the tubes (e.g., the Stone & Webster design discussed above) are used to reduce the problem of lowered boil-off rates caused by crystallization, salting, and scaling.

About two-thirds of the plants report achieving decontamination factors that are less than the design estimates, frequently 1/10 of design, but in several instances 1/1000 to 1/10,000 of design. Decontamination factors for several operating power plants are shown in Fig. 8, and performance data²⁰ for the evaporator at Oyster Creek are given in Table 4. Results from a performance test²¹ on the waste evaporator at H. B. Robinson Unit No. 2 are

presented in Appendix E. Except for the small, 10-year-old evaporator at Humboldt Bay and the unmodified unit at Point Beach, the average system DF's shown in Fig. 8 are greater than approximately 10^3 . The average system DF's for the Oyster Creek evaporator (Table 4) range from 10^3 to mid 10^5 . A recent survey²² of radwaste from nuclear power plants in West Germany indicated that a realistic average system DF for a waste evaporator is 10^2 - 10^3 . Apparently, no differentiation is made between nonvolatile and volatile solutes or aqueous and nonaqueous solutions.

The problem of increasing decontamination factors, where they are less than design estimates, is being approached in several ways at nuclear power plants. One way is improved evaporator control systems, including improved liquid-level detectors, foam sensors, and pressure controllers (in particular, the vacuum units). Another way is modification or replacement of entrainment separators so that they match or complement the evaporator's performance as discussed in Sect. 6 and Appendix C. Still another and very important way is increased attention to the evaporator operation by trained personnel.

7.3 AEC-Operated Facilities

Evaporation has been widely and routinely used at AEC-operated facilities with satisfactory results for over two decades. Descriptions and typical performance results of the evaporators at several of these installations are summarized in Table 5, Fig. 9, and Appendices F-H. The average system DF's shown in Fig. 9 range from mid 10^2 to mid 10^6 . An interesting observation to be made concerning the performance results (Appendix H) for the ORNL waste evaporator is that in a given run the DF's for all isotopes are, within a factor of about two, the same. However, the waste did not contain iodine for comparison of its DF's with nuclear power plant results. In general, the evaporators have performed at or slightly below design rates and DF's.

Consideration of all the information collected in this study leads to the conclusion that evaporation is very effective in separating non-volatile radioactive contaminants from waste water. It can be useful for

rapidly cleaning up large volumes of highly contaminated water, either routinely or in emergencies. Materials having vapor pressures that are higher than water (organic materials) are not separated from water by evaporation. Materials with moderately high vapor pressures (iodine and ruthenium) are not separated effectively from water under some conditions. An average system decontamination factor of 10^3 to 10^4 can be expected for nonvolatile radioactive contaminants treated in single-stage evaporators. Similar $(\overline{DF})_s$'s can be expected for ruthenium under alkaline, but not acidic and oxidizing, conditions. The $(\overline{DF})_s$'s for iodine can be expected to be a factor of 10 to 100 lower than those expected for nonvolatile species under alkaline, but not oxidizing or acidic, conditions. The $(\overline{DF})_s$'s for wastes that contain soaps and detergents can be expected to be a factor of 10 to 100 lower than those expected when such organic materials are absent. These values assume that the evaporator is well designed, adequately sized, and operated with reasonable skill. Higher decontamination factors can be achieved but require simultaneous optimization of (1) pH and redox potential of the feed to ensure that all solutes are nonvolatile; (2) evaporator design and operating conditions to minimize foam, splashover, and entrainment; and (3) the operator's skill and attention to ensure that conditions (1) and (2) are maintained.

8.0 ACKNOWLEDGMENTS

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APPENDIX A. EXAMPLES OF EVAPORATOR TYPES USED AND
PROPOSED FOR USE IN THE NUCLEAR POWER INDUSTRY

ORNL DWG-72-1393 R1

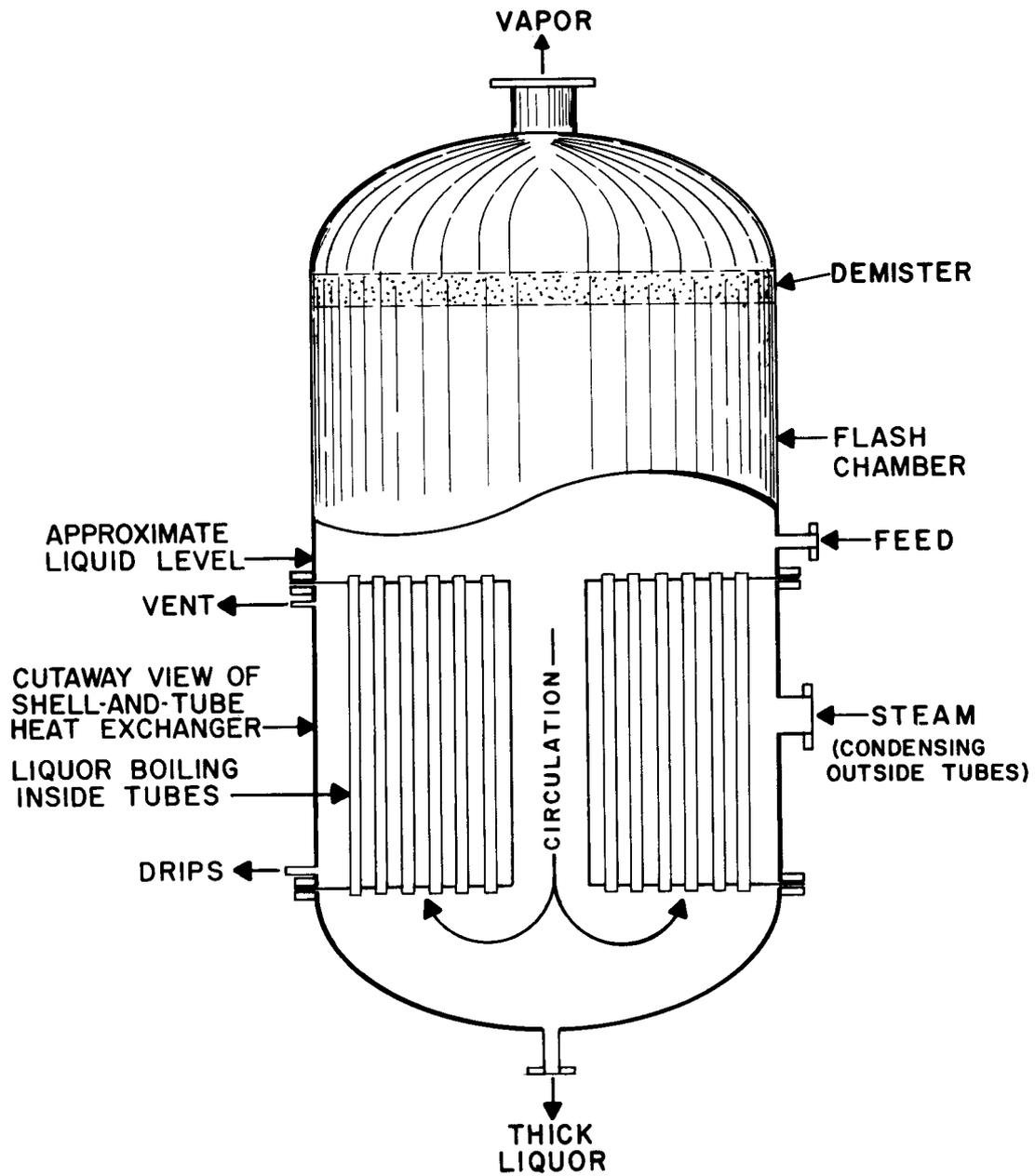


Fig. A-1. Short Vertical-Tube (Calandria or Standard) Evaporator.

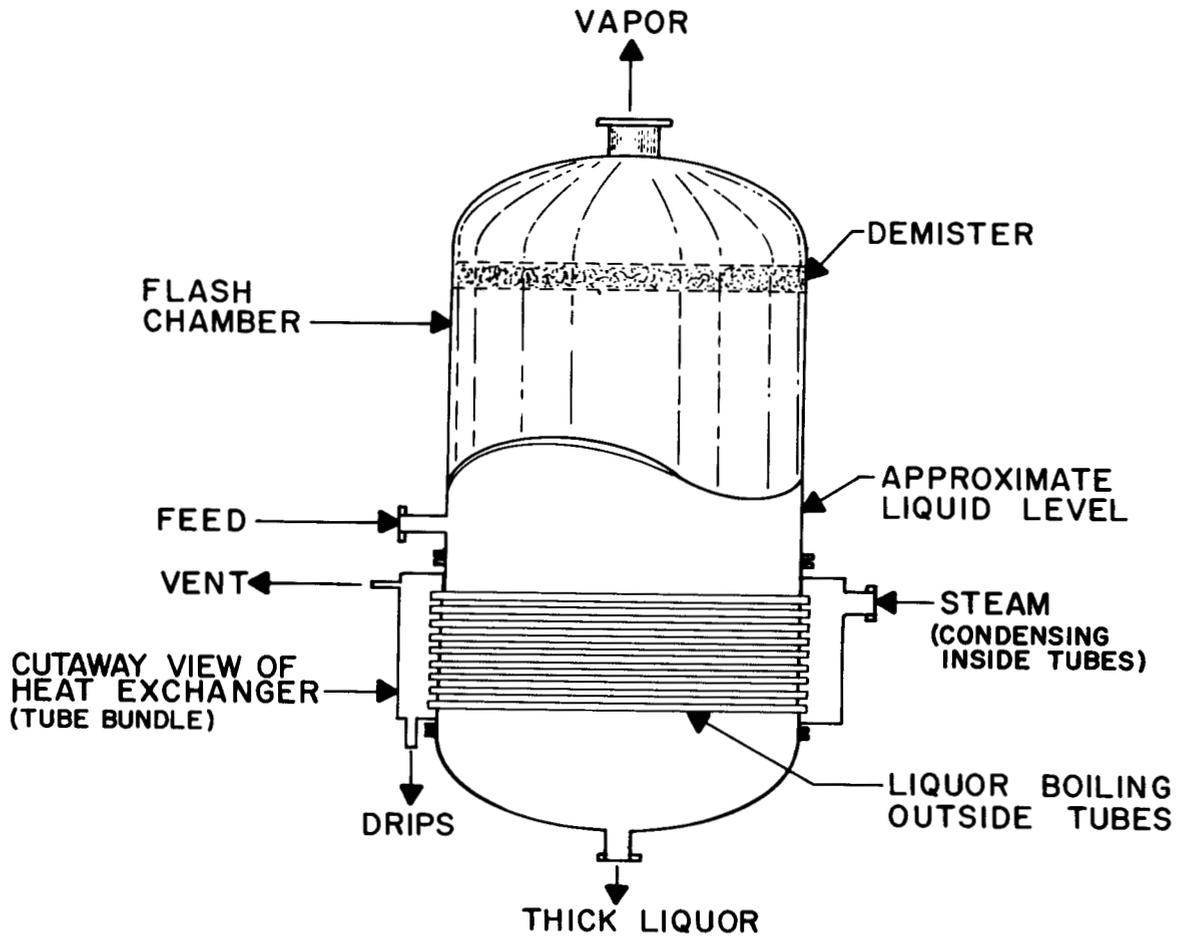


Fig. A-2. Horizontal-Tube Evaporator (Classic Construction).

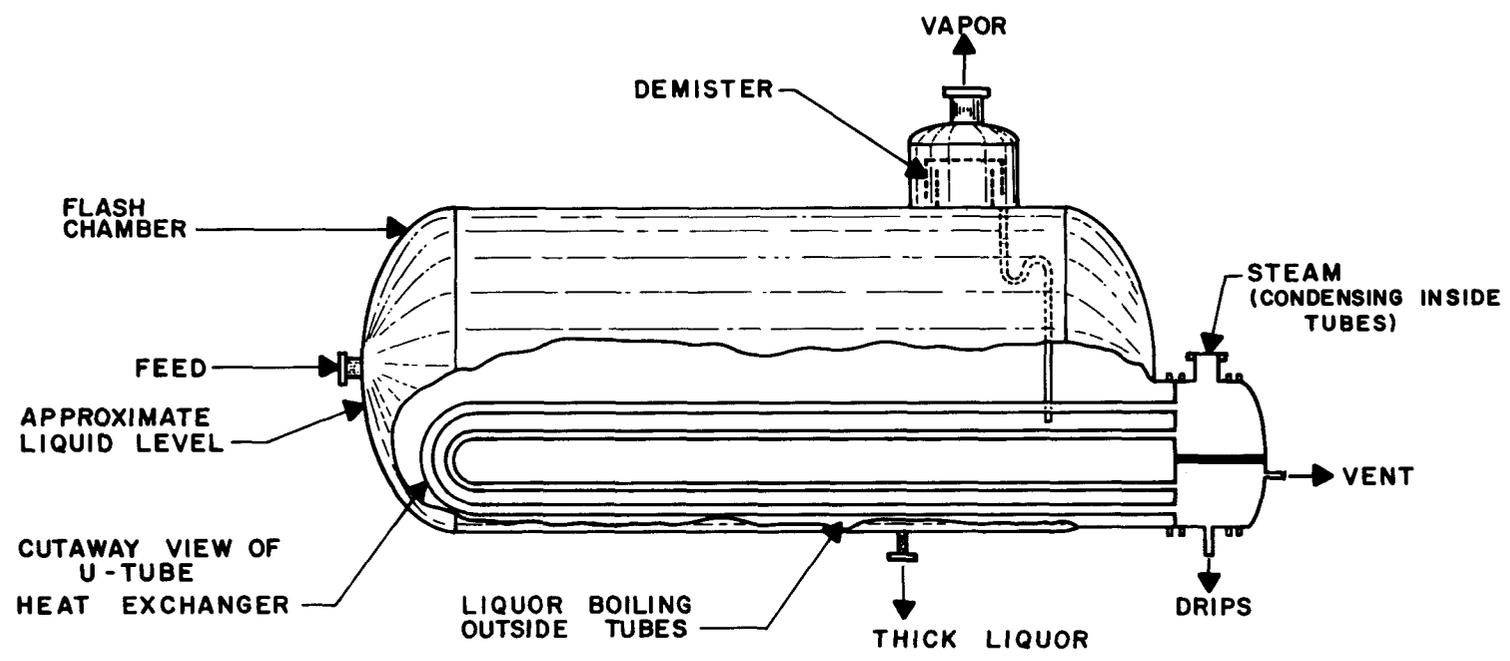


Fig. A-3. Horizontal-Tube Evaporator with U-Bend Tubes. (Feed may be sprayed onto tubes for breaking foam.)

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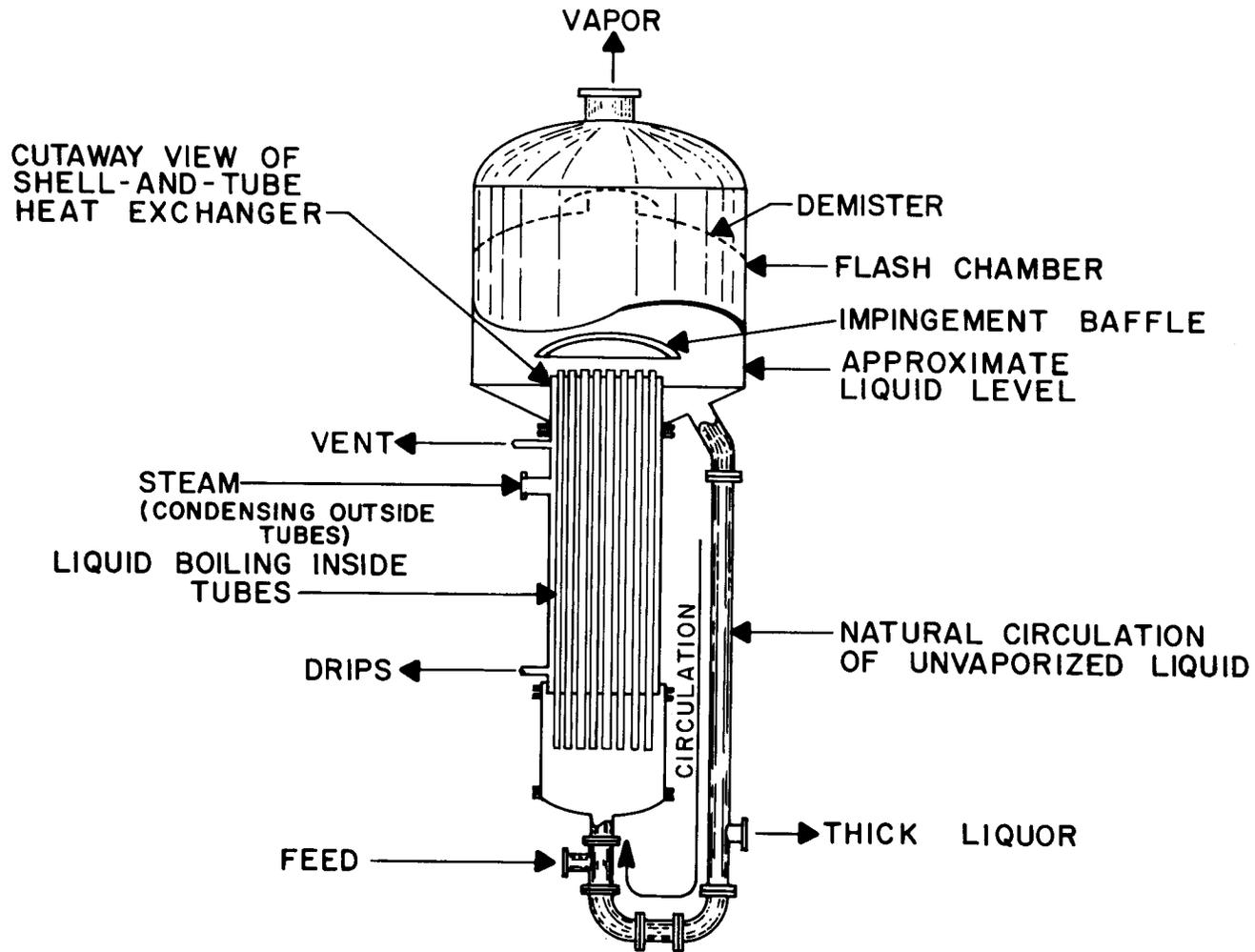


Fig. A-4. Long Vertical-Tube Evaporator with Natural Circulation.

ORNL DWG 72-1395R2

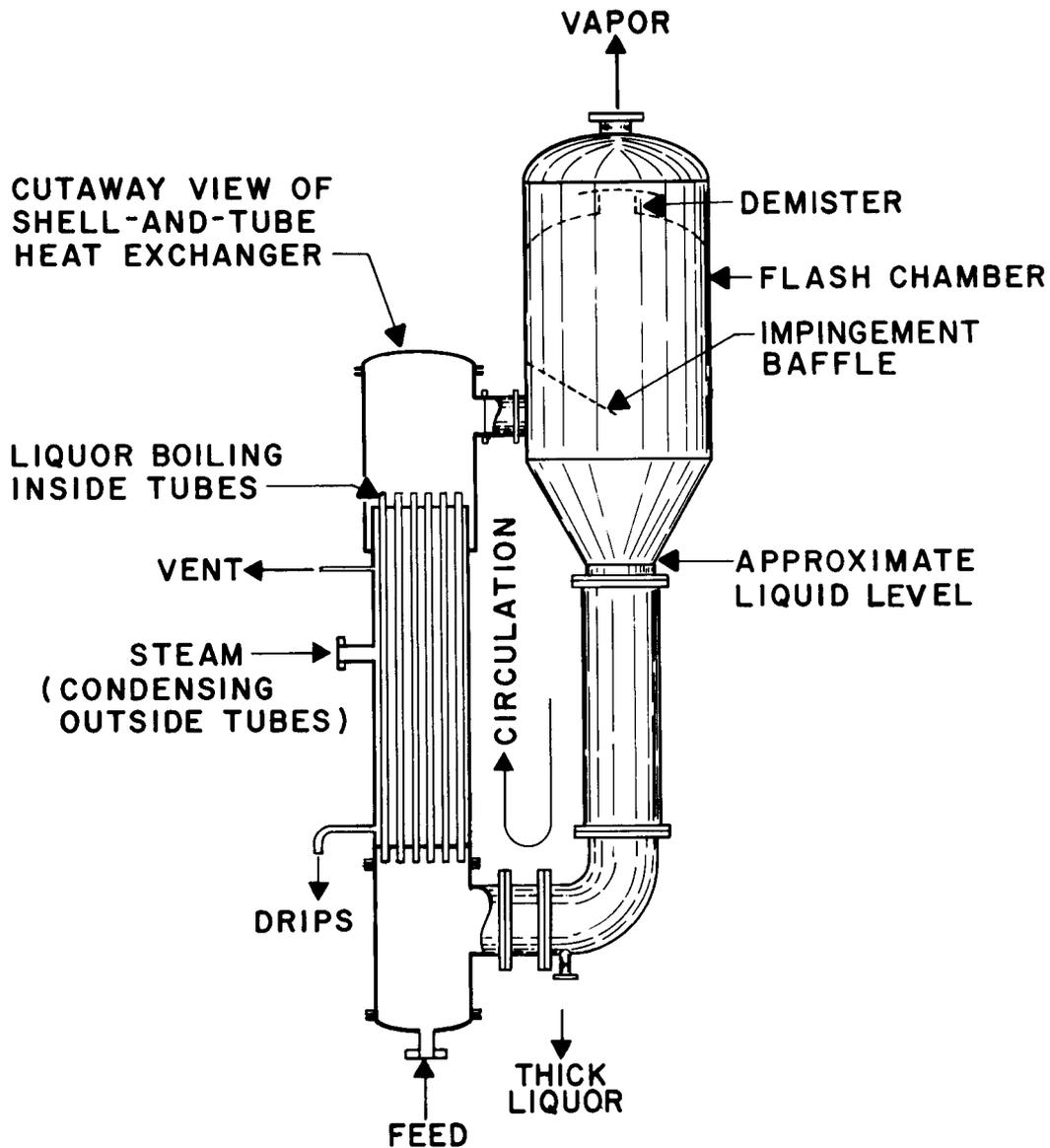


Fig. A-5. Long Vertical-Tube Evaporator with External Heater and Natural Circulation (Thermosiphon).

ORNL DWG. 73-5932

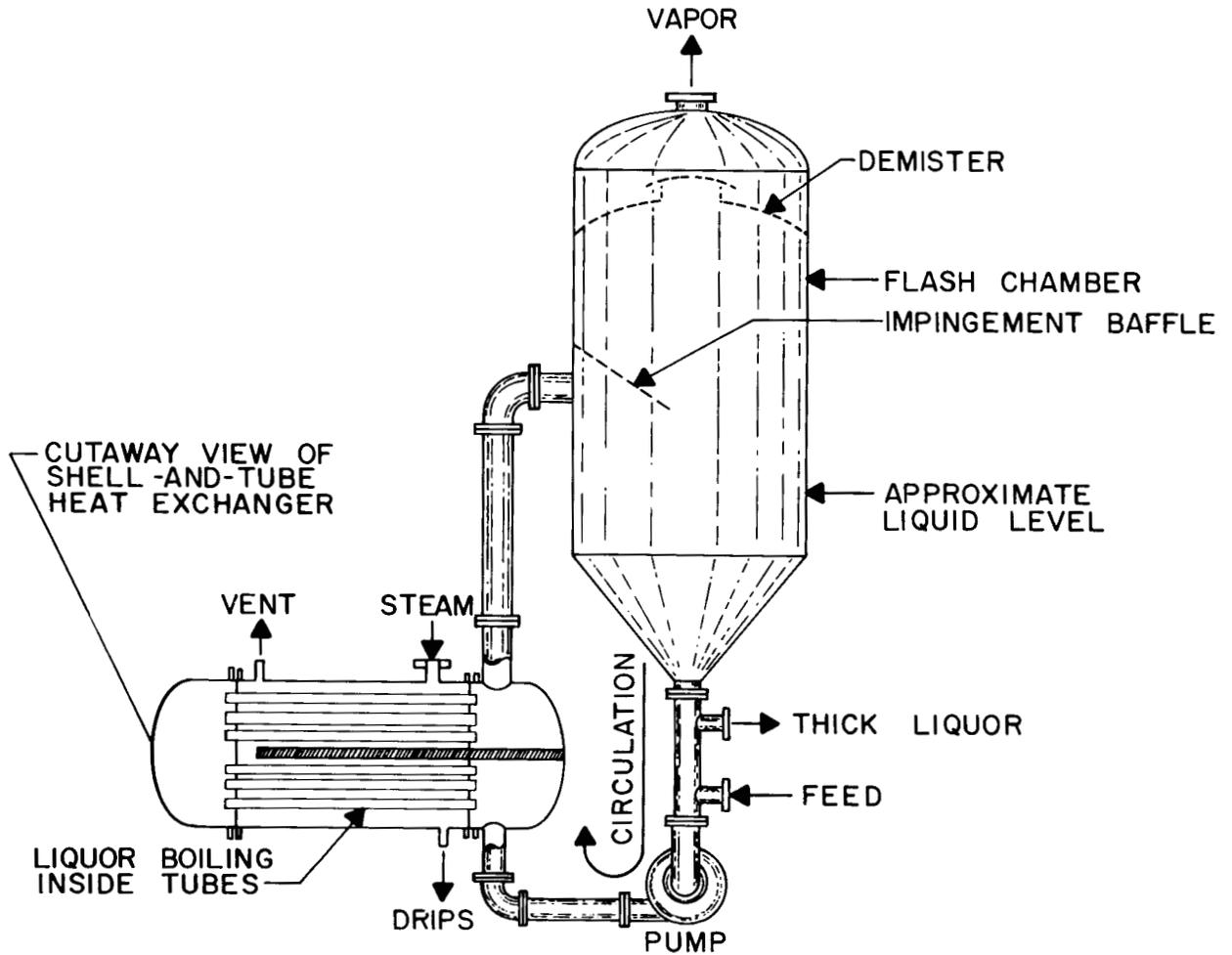
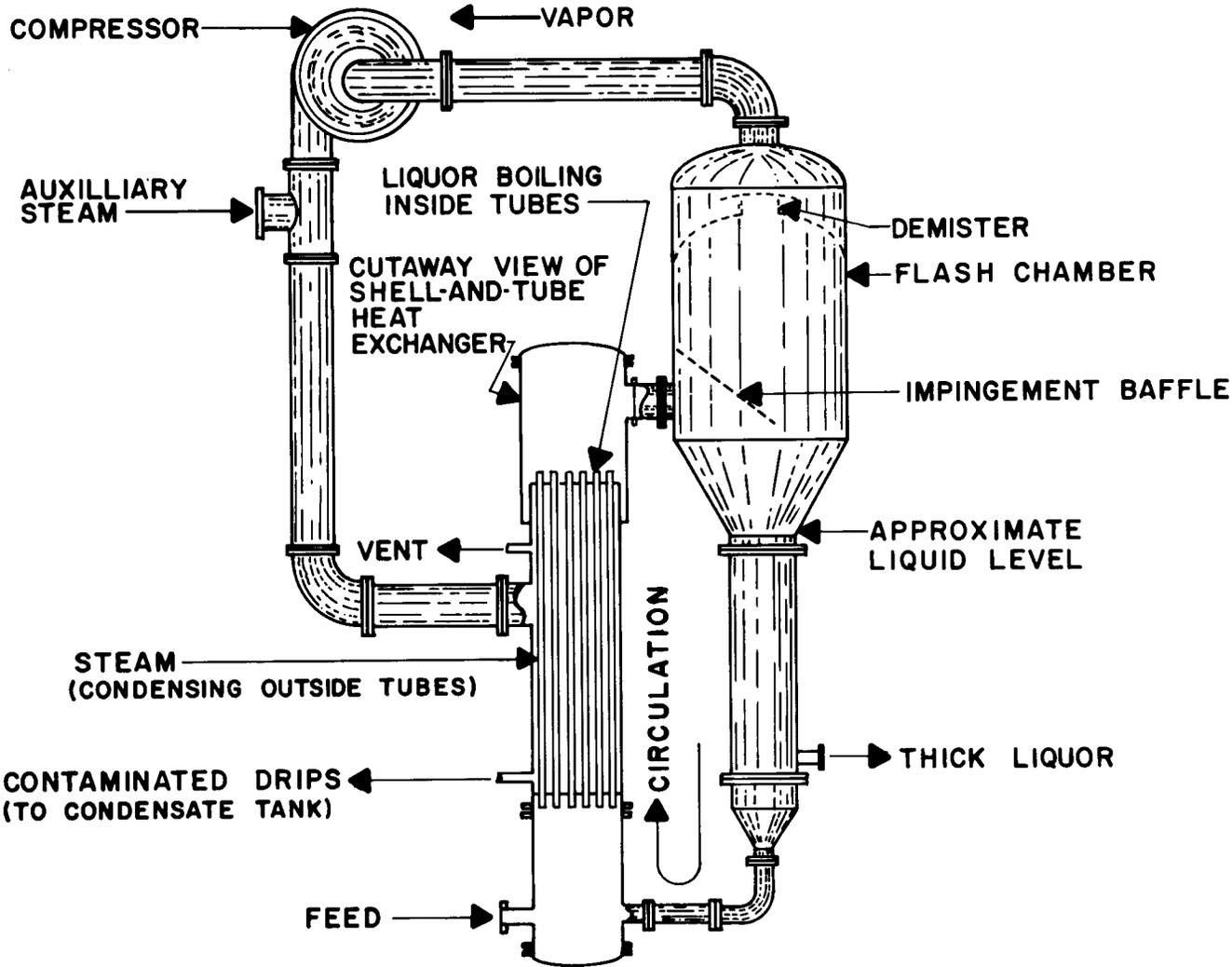
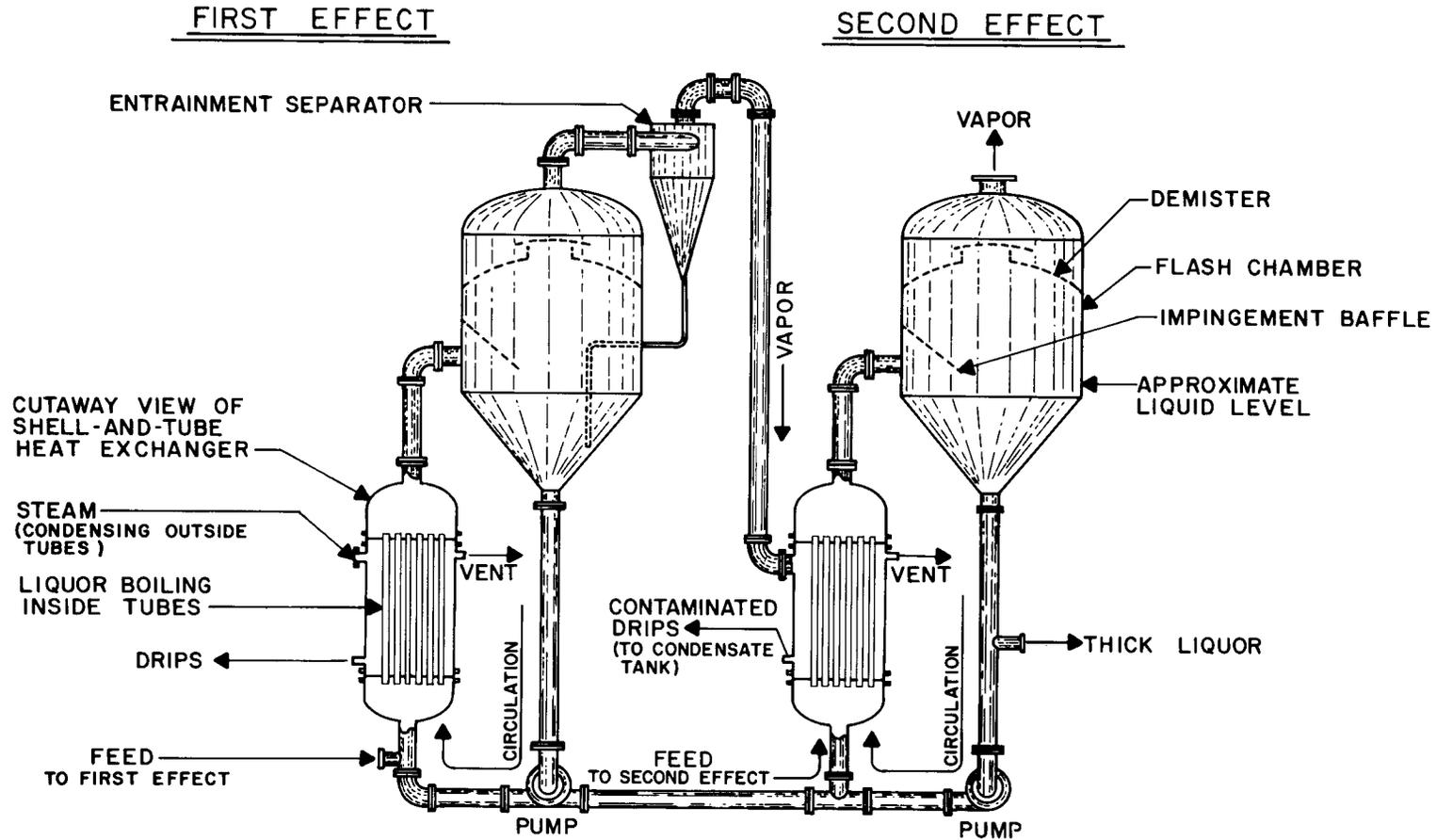


Fig. A-6. Forced-Circulation Evaporator with an External Horizontal Heater.



44

Fig. A-7. Vapor-Compression Evaporator. (Mechanical devices and steam injectors are used to compress the vapor arising from the flash chamber.)



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Fig. A-8. Double-Effect Evaporator with External Vertical Heaters, Forced Circulation, and Forward Feed. (In a forward-feed system, the feed and vapor are parallel.)

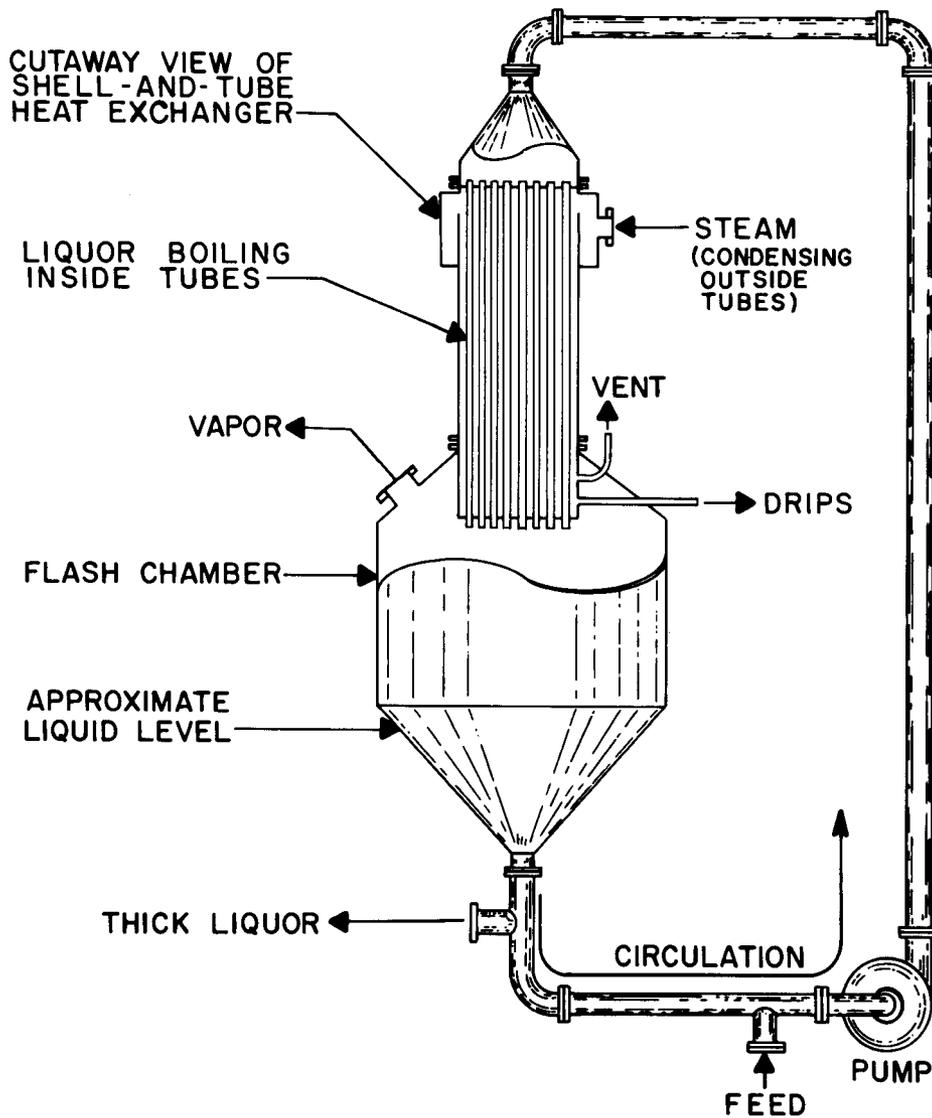


Fig. A-9. Falling-Film Evaporator with Forced Circulation.

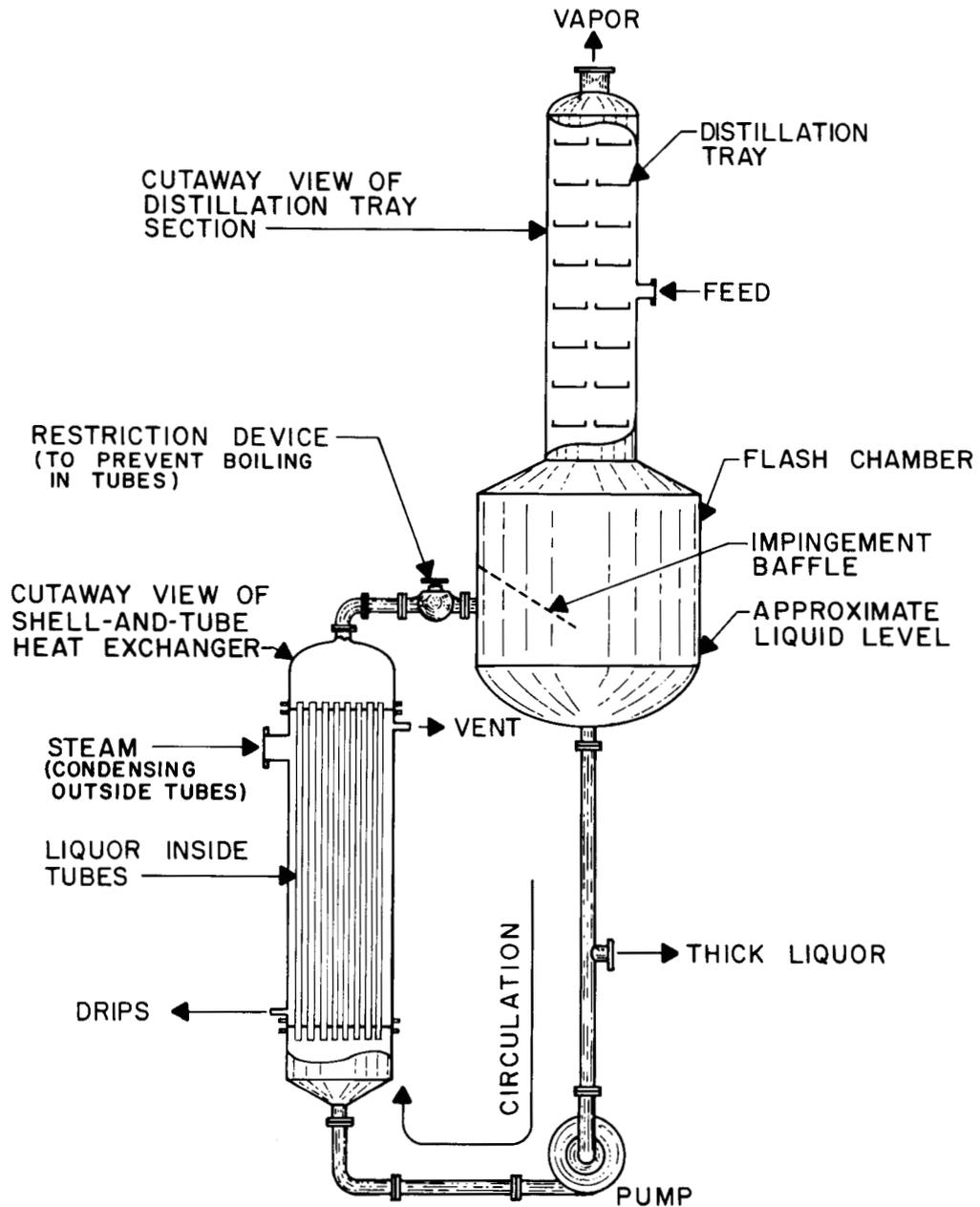


Fig. A-10. Long Vertical-Tube Evaporator with External Heater, Forced Circulation, Restriction Device to Prevent Boiling in Tubes, and Distillation Tray Section.

ORNL DWG. 73-5935

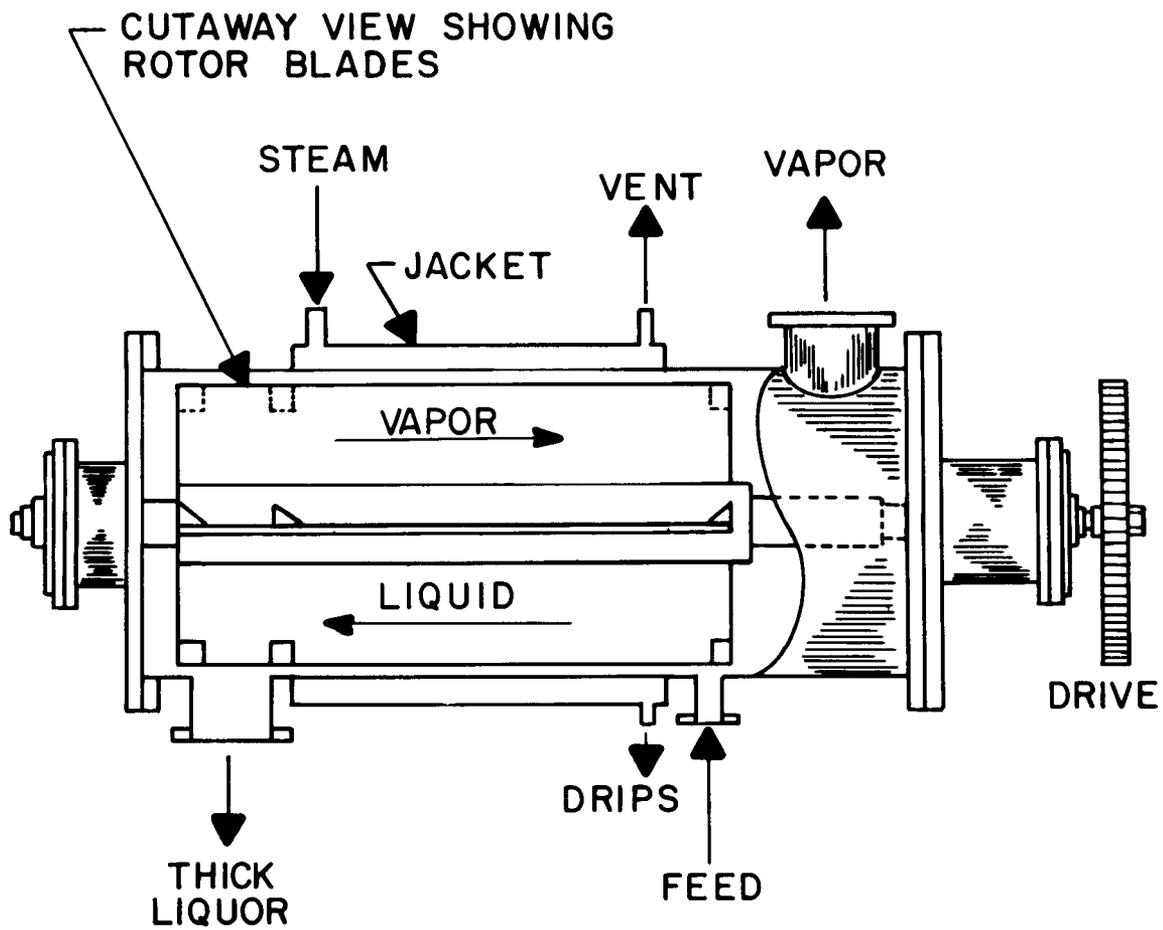


Fig. A-11. Turbulent-Film Evaporator. (This type evaporator is also called thin-, agitated-, and wiped-film. Units may be horizontal or vertical and the heated walls may be tapered.)

APPENDIX B. INTERRELATIONSHIPS BETWEEN SYSTEM AND EQUIPMENT
DECONTAMINATION FACTORS FOR CONTINUOUS, BATCH, AND
SEMICONTINUOUS MODES OF EVAPORATOR OPERATION

The instantaneous decontamination factor for an evaporator $(DF)_{ei}$, also called equipment DF, is defined as the ratio of the thick liquor concentration at any time, C_{lt} , to the condensate concentration at any time, C_{ct} , as given by the equation

$$(DF)_{ei} = \frac{C_{lt}}{C_{ct}} . \quad (B-1)$$

The instantaneous decontamination across the evaporator system, $(DF)_{si}$, often called the process DF, is defined as the ratio of the feed concentration at any time, C_{ft} , to the condensate concentration at any time as given by the equation

$$(DF)_{si} = \frac{C_{ft}}{C_{ct}} . \quad (B-2)$$

With a constant feed concentration, C_f , the concentration factor at any time, $(CF)_t$, is given by the equation

$$(CF)_t = \frac{C_{lt}}{C_f} . \quad (B-3)$$

Combination of Eqs. (B-1), (B-2), and (B-3) shows the relationship between $(DF)_{ei}$ and $(DF)_{si}$ to be

$$(DF)_{ei} = (DF)_{si} \times (CF)_t . \quad (B-4)$$

For an evaporator operated in a continuous mode (as defined in Sect. 4), Eqs. (B-1), (B-2), and (B-4) also give the average DF's since, for an evaporator operated in a continuous mode, concentrations are not time dependent. The concentration factor is the feed rate divided by the thick liquor rate.

For an evaporator operated in a batch mode (as defined in Sect. 4), if the concentration of the thick liquor is reasonably linear with volume,

the average thick liquor concentration, \bar{C}_1 , is equal to one-half the sum of the original feed concentration, C_{fo} , and the final thick liquor concentration, C_{1f} , as given by the equation

$$\bar{C}_1 = \frac{C_{fo} + C_{1f}}{2} . \quad (B-5)$$

The final volume reduction factor, $(VR)_f$, for a batch evaporation is the ratio of the volume of feed originally charged to the evaporator, V_{fo} , to the final volume of thick liquor removed from the evaporator, V_{1f} , as given by the equation

$$(VR)_f = \frac{V_{fo}}{V_{1f}} . \quad (B-6)$$

The thick liquor concentration at any time as obtained from a material balance across the evaporator, where V_c represents the volume of condensate and \bar{C}_c the average condensate concentration, is given by the relation

$$C_{1f} = C_{fo} \left(\frac{V_{fo}}{V_{1f}} \right) - \bar{C}_c \left(\frac{V_c}{V_{1f}} \right) . \quad (B-7)$$

The average equipment DF, $(\overline{DF})_e$, for a batch evaporation is the ratio of the average thick liquor concentration to the average condensate concentration as given by the equation

$$(\overline{DF})_e = \frac{\bar{C}_1}{\bar{C}_c} . \quad (B-8)$$

Substitution of Eqs. (B-5) and (B-7) into Eq. (B-8) shows that the average equipment DF, $(\overline{DF})_e$, for a batch evaporation is equal to

$$(\overline{DF})_e = \frac{1}{2} \frac{C_{fo}}{\bar{C}_c} \left[1 + (VR)_f - \frac{\bar{C}_c}{C_{fo}} \left(\frac{V_c}{V_{1f}} \right) \right] . \quad (B-9)$$

If the solution volumes are additive, V_c equals V_{fo} minus V_{1f} and Eq. (B-9) may be written as

$$(\overline{DF})_e = \frac{1}{2} \frac{C_{fo}}{C_c} \left\{ 1 + (VR)_f - \frac{\overline{C}_c}{C_{fo}} \left[(VR)_f - 1 \right] \right\}. \quad (B-10)$$

In most practical cases, the last term in Eqs. (B-9) and (B-10) is small and $(\overline{DF})_e$ is given as

$$(\overline{DF})_e = \frac{1}{2} \frac{C_{fo}}{C_c} \left[1 + (VR)_f \right]. \quad (B-11)$$

The average system DF, $(\overline{DF})_s$, for a batch evaporation is the ratio of the original feed concentration to the average condensate concentration as given by the equation

$$(\overline{DF})_s = \frac{C_{fo}}{C_c}. \quad (B-12)$$

Substitution of Eq. (B-12) into Eqs. (B-9), (B-10), and (B-11) shows the relationship between $(\overline{DF})_e$ and $(\overline{DF})_s$ for a batch evaporation to be

$$(\overline{DF})_e = \frac{1}{2} (\overline{DF})_s \left[1 + (VR)_f - \frac{1}{(\overline{DF})_s} \left(\frac{V_c}{V_{1f}} \right) \right], \quad (B-13)$$

$$(\overline{DF})_e = \frac{1}{2} (\overline{DF})_s \left\{ 1 + (VR)_f - \frac{1}{(\overline{DF})_s} \left[(VR)_f - 1 \right] \right\}, \text{ or} \quad (B-14)$$

$$(\overline{DF})_e = \frac{1}{2} (\overline{DF})_s \left[1 + (VR)_f \right] \quad (B-15)$$

with the respective assumptions given above.

For an evaporator operated in a semicontinuous mode (as defined in Sect. 4) with feed of constant composition, C_f , if the thick liquor concentration is reasonably linear with time, the average thick liquor concentration is given by Eq. (B-5) and the average equipment DF by Eq. (B-8).

The overall volume reduction factor, $(VR)_o$, for a semicontinuous evaporation is the ratio of the total volume of feed processed, V_{fp} , to

the inventory of thick liquor, V_1 , in the evaporator as given by the equation

$$(VR)_o = \frac{V_{fp}}{V_1} . \quad (B-16)$$

The thick liquor concentration at any time as determined by a material balance across the evaporator is given by the equation

$$C_{1f} = C_f \left(\frac{V_{fp}}{V_1} \right) - \bar{C}_c \left(\frac{V_c}{V_1} \right) . \quad (B-17)$$

Substitution of Eqs. (B-5) and (B-17) into Eq. (B-8) shows that the average equipment DF for a semicontinuous evaporation is given by the relation

$$(\overline{DF})_e = \frac{1}{2} \frac{C_f}{C_c} \left[1 + (VR)_o - \frac{\bar{C}_c}{C_f} \left(\frac{V_c}{V_1} \right) \right] . \quad (B-18)$$

If the solution volumes are additive, V_c equals V_{fp} minus V_1 and Eq. (B-18) may be expressed as

$$(\overline{DF})_e = \frac{1}{2} \frac{C_f}{C_c} \left\{ 1 + (VR)_o - \frac{\bar{C}_c}{C_f} \left[(VR)_o - 1 \right] \right\} . \quad (B-19)$$

In most evaporations the last term in Eqs. (B-18) and (B-19) is small and $(\overline{DF})_e$ is given as

$$(\overline{DF})_e = \frac{1}{2} \frac{C_f}{C_c} \left[1 + (VR)_o \right] . \quad (B-20)$$

The average system DF for a semicontinuous evaporation is the ratio of the feed concentration to the average condensate concentration as given by the equation

$$(\overline{DF})_s = \frac{C_f}{C_c} . \quad (B-21)$$

Substitution of Eq. (B-21) into Eqs. (B-18), (B-19), and (B-20) shows the relationship between $(\overline{DF})_e$ and $(\overline{DF})_s$ for a semicontinuous evaporation to be

$$(\overline{DF})_e = \frac{1}{2} (\overline{DF})_s \left[1 + (VR)_o - \frac{1}{(\overline{DF})_s} \left(\frac{V_c}{V_1} \right) \right], \quad (B-22)$$

$$(\overline{DF})_e = \frac{1}{2} (\overline{DF})_s \left\{ 1 + (VR)_o - \frac{1}{(\overline{DF})_s} \left[(VR)_o - 1 \right] \right\}, \text{ or} \quad (B-23)$$

$$(\overline{DF})_e = \frac{1}{2} (\overline{DF})_s \left[1 + (VR)_o \right] \quad (B-24)$$

with the respective assumptions given above.

APPENDIX C. CORRELATION OF ENTRAINMENT LOSSES

The empirical correlation¹² depicted in Fig. C-1 shows a decrease in DF with increasing boilup rate. The curve is an average of available data and gives evaporator decontamination factor as a function of a correlating constant. This constant, inferred from Stoke's settling law, is a measure of the droplet size that will be carried over by the vapor and may be expressed as

$$E = u_g [\rho_g / (\rho_l - \rho_g)]^{1/2}, \quad (C-1)$$

where

- E = entrainment factor, ft/hr,
- u_g = linear vapor velocity, ft/hr, calculated at the largest horizontal cross-sectional area for vapor flow,
- ρ_g = vapor density, lb/ft³,
- ρ_l = thick liquor density, lb/ft³.

These $(DF)_e$'s are for the evaporator (calandria plus flash chamber plus impingement plate or baffle) and do not include external entrainment separators such as wire packed columns, cyclones, and trays. Decontamination factor correlations are presented also, e.g., ref. 4, as plots of DF vs $u_g \rho_g^{1/2}$ and DF vs $u_g \rho_g$, where ρ_g is the density of the vapor and u_g is the linear velocity of the vapor as defined above. Most evaporators have devices incorporated or attached to remove entrained liquid droplets. The overall decontamination factor for the evaporator plus deentrainment devices may differ widely from the DF for the evaporator alone as illustrated in Fig. C-2. The results shown in Fig. C-1 could imply that at lower boilup rates the decontamination factor would be higher. But, results^{4,11,13,14} have shown that at very low boilup rates the decontamination factor decreases with decreasing boilup rate (cf. Fig. C-2).

As an example of the application of the correlation shown in Fig. C-1, consider the information given in ref. 8 for the 2-gpm AMF Model 120 Ray-Dipak Evaporator installed at the Ginna Station: operating pressure equal to about 3 psia and vapor linear velocity equal to about

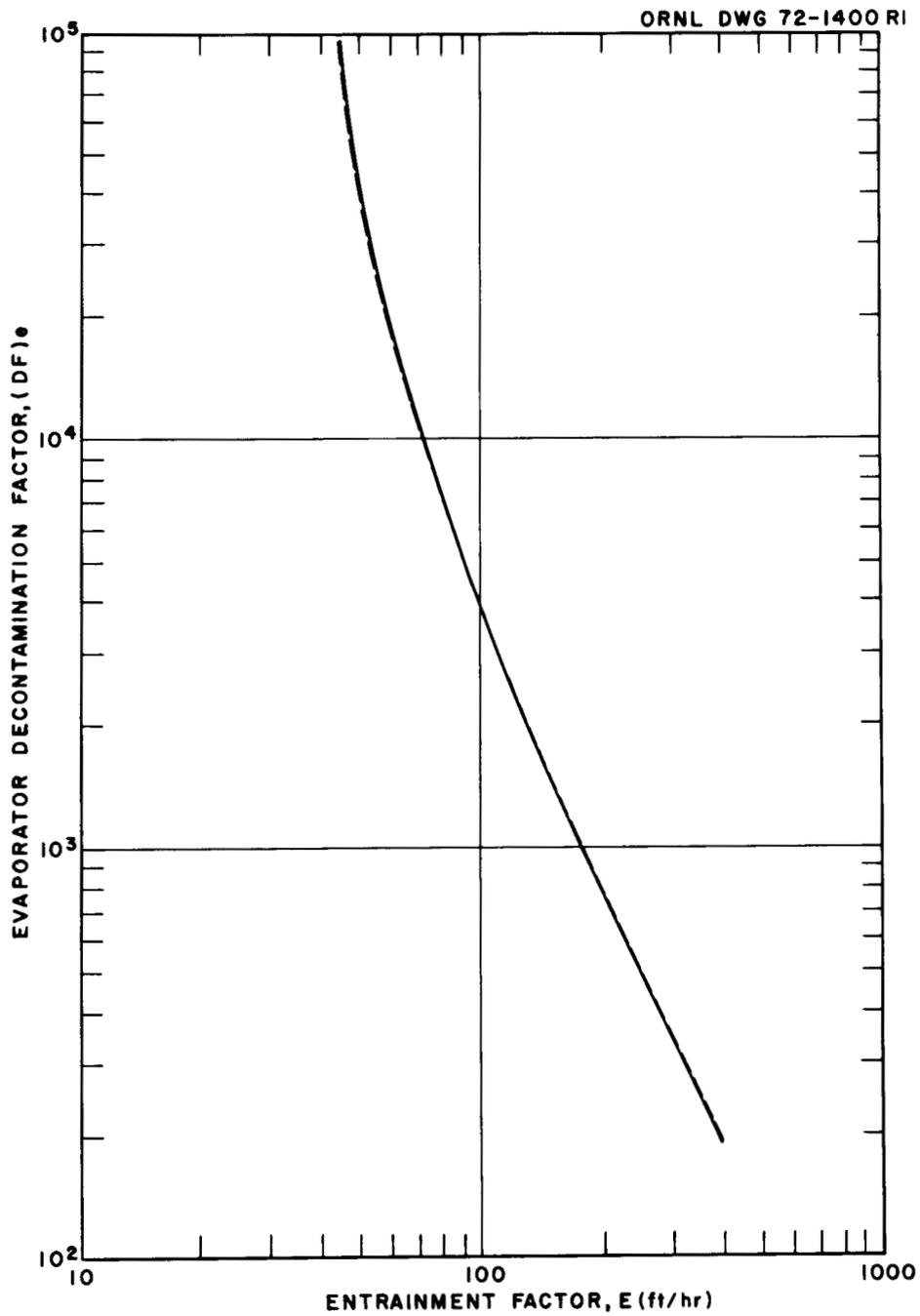


Fig. C-1. Evaporator Decontamination Factor, $(DF)_e$, vs Entrainment Factor, E . (Redrawn from ref. 12)

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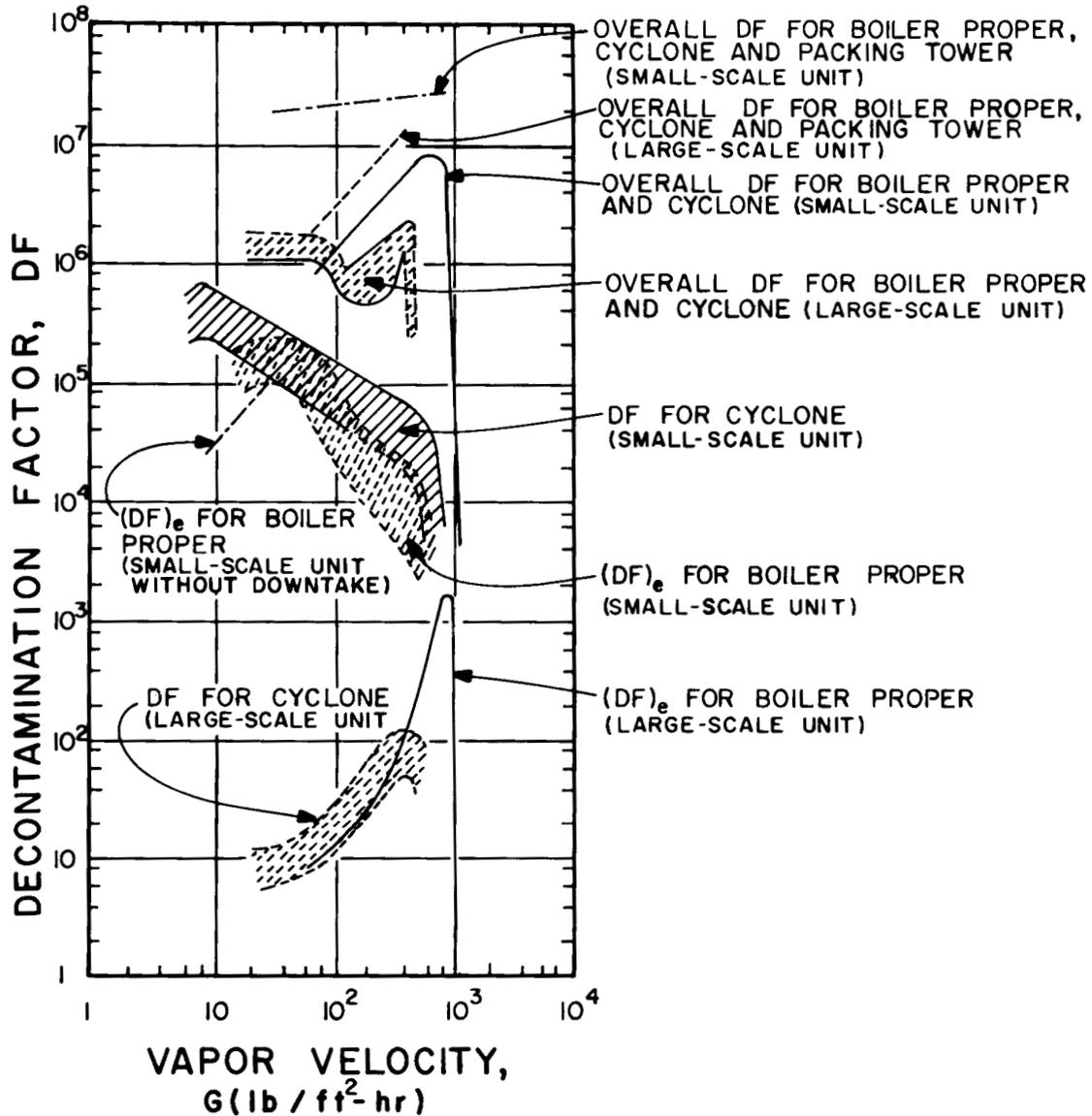


Fig. C-2. Overall Decontamination Factor of Evaporator and Entrainment Separators vs Mass Velocity of Vapor. (Redrawn from ref. 11)

6 ft/sec or 21,600 ft/hr. At 3 psia the value of ρ_g is 0.0084 lb/ft³ (steam tables). If the thick liquor has a density of about 75 lb/ft³ at the conditions (~ 3 psia and $\sim 142^\circ\text{F}$) in the evaporator, E may be evaluated from Eq. (C-1) as

$$E = 21,600 [0.0084/(75 - 0.0084)]^{1/2}$$

or

$$E = 229 \text{ ft/hr.}$$

From Fig. C-1, at this value of E, $(DF)_e$ equals about 6×10^2 . This DF would be for the evaporator and would not include DF's for the perforated plate, sieve tray, and mesh in the deentrainment section of the evaporator (Fig. 4). The values of equipment DF's for this evaporator as originally installed were reported¹⁵ to be from 3.2×10^2 to 10^3 as determined from operating experience. Design specifications called for an equipment DF of 10^6 . The evaporator system was modified (Sect. 6.1) and recent operating results¹⁶ show equipment DF's from low 10^4 to mid 10^5 .

APPENDIX D. OAK RIDGE NATIONAL LABORATORY (ORNL) STUDIES IN
SMALL-SCALE EQUIPMENT ON THE DECONTAMINATION OF LIQUID
RADWASTE BY EVAPORATION

A series of experiments was carried out to study the decontamination factor (DF) obtained during evaporation of radwastes. The wastes studied were a simulated ORNL intermediate-level radioactive waste and a simulated radioactive borate waste with the compositions given in Table D-1. A schematic of the small-scale equipment used in these studies is shown in Fig. D-1. The average system decontamination factors, $(\overline{DF})_s$'s, achieved are low 10^4 for cesium (Figs. D-2 and D-8), sodium (Fig. D-3), and strontium (Fig. D-4); are in the range of mid 10^3 to low 10^4 for ruthenium (Figs. D-5 and D-9); and are in the range of mid 10 to 10^2 for iodine (Figs. D-6 and D-10) with the wastes as made up in Table D-1. Speaking broadly, the system decontamination factor obtained in an evaporation with this equipment is fairly steady with volume reduction factor (ratio of the volumes of feed processed to the volume of thick liquor) and the equipment decontamination factor increases with increasing volume reduction factor (Figs. D-2 through D-17).

A possible explanation of the low DF's for iodine shown in Figs. D-6 and D-10 is the very low concentration of iodine compared to the concentration of low-molecular-weight organics in the solutions (viz., organics in the tap water used to prepare solutions, sorbed from the air, and leached from plastic containers used in preparing and for storing the solutions). In other words, the ratio of the concentration of trace organics to the concentration of tracer iodine (the only iodine added in the above two experiments) is high and the probability of forming organic iodides with most or all of the tracer is high. To reduce the amount of radioactive iodine in organic iodides, an iodide salt containing only nonradioactive iodine was added to the wastes - a technique frequently called isotopic dilution. After the addition of 0.2 $\mu\text{Ci/ml}$ of ^{131}I and 0.01 g-mole/liter of nonradioactive potassium iodide to the wastes as shown in Table D-1, the average system DF for iodine increased to mid 10^3 - 10^4 with the ORNL ILW (cf. Fig. D-6 to Fig. D-7) and increased to low 10^4 with the borate waste (cf. Fig. D-10 to Figs. D-11 and D-12).

To determine the effect of a large amount of an organic known readily to form iodides on the above iodine DF's, 0.5 g/liter of diethylbenzene was added to the borate waste in addition to the 0.2 $\mu\text{Ci}/\text{ml}$ of ^{131}I and 0.01 g-mole/liter of KI. The average system DF's obtained in these experiments (Figs. D-13 and D-14) were about half those without the diethylbenzene, i.e., in the range of low to mid 10^3 . An increase in the amount of KI to 0.02 g-mole/liter of borate waste, while maintaining the $(\text{C}_2\text{H}_5)_2\text{C}_6\text{H}_4$ at 0.5 g/liter and the tracer iodine at 0.2 $\mu\text{Ci}/\text{ml}$, lowered the average system DF's to about mid 10^2 (Figs. D-15 and D-16).

A possible explanation of the latter result with KI addition is that the concentration of iodide in the aqueous phase was increased beyond a value at which it could all be maintained in the nonvolatile iodide state. That is to say, elemental iodine was probably volatilized from the waste. To test this supposition, sodium sulfite was selected as a reductant to adjust the redox potential of the waste. To the borate waste containing 0.2 $\mu\text{Ci}/\text{ml}$ of ^{131}I , 0.5 g/liter of $(\text{C}_2\text{H}_5)_2\text{C}_6\text{H}_4$, and 0.02 g-mole/liter of KI, was added 0.1 g-mole/liter of Na_2SO_3 . The average system DF's of mid 10^2 obtained without sulfite addition increased to mid 10^3 with sulfite addition (cf. Figs. D-16 and D-17).

In these experiments, relatively large amounts of additives were employed since the purpose was to illustrate gross effects. In-depth studies to determine the amount of additive for maximum enhancement of iodine DF and minimum solids loading of the evaporator are needed. Basic physicochemical studies to better define the behavior of iodine during the evaporation of inorganic and organic liquids are desirable.

Table D-1. Composition and Properties of Simulated Liquid Radwastes Used in ORNL Evaporation Studies

	Concentration ^a (g-mole/liter)	
	ORNL ILW ^b	Borate Waste
Constituents		
Na ⁺	0.55	0.128
Cs ⁺	0.0082	
NH ₄ ⁺	0.001	
H ⁺		0.0693
Ca ²⁺	0.0017	
Sr ²⁺	0.0023	
Al ³⁺	0.0025	
Cl ⁻	0.031	
OH ⁻	0.06	0.128
NO ₃ ⁻	0.295	
CO ₃ ²⁻	0.0633	
SO ₄ ²⁻	0.0313	
BO ₃ ³⁻		0.0231
Property		
pH	10.9	12.8
Electrical conductivity	6.9 x 10 ⁻³ mho/cm	22 x 10 ⁻³ mho/cm

^aAs made up.

^bOak Ridge National Laboratory (ORNL) Intermediate-Level Waste (cf. Appendix H).

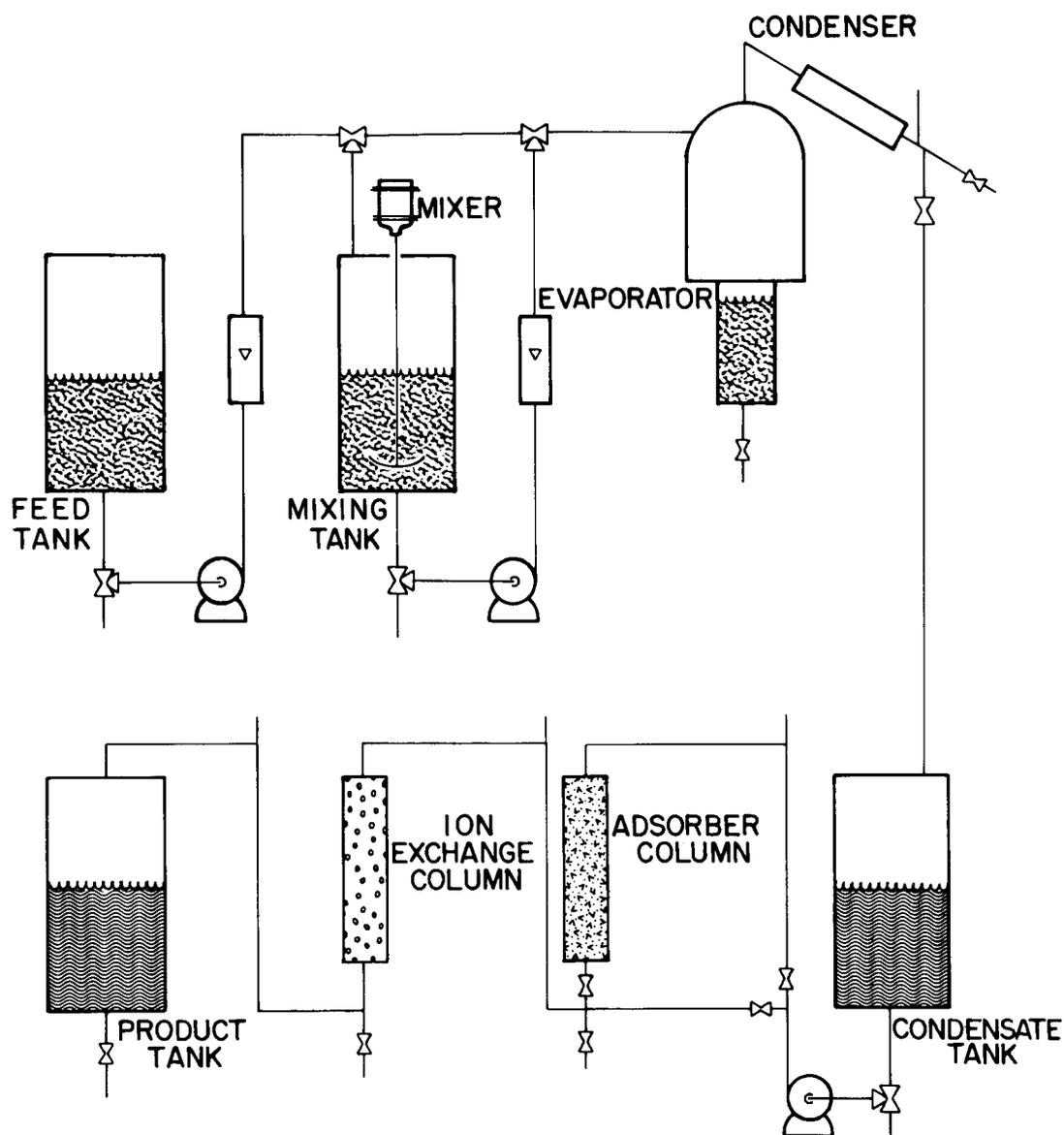


Fig. D-1. Schematic of 3-kW Evaporator Used in Laboratory Studies on Decontamination of Simulated Radioactive Wastes. Evaporator pot is 3 in. ID x 6 in. high and flash chamber is 6 in. ID x 8 in. high. (See ref. 23)

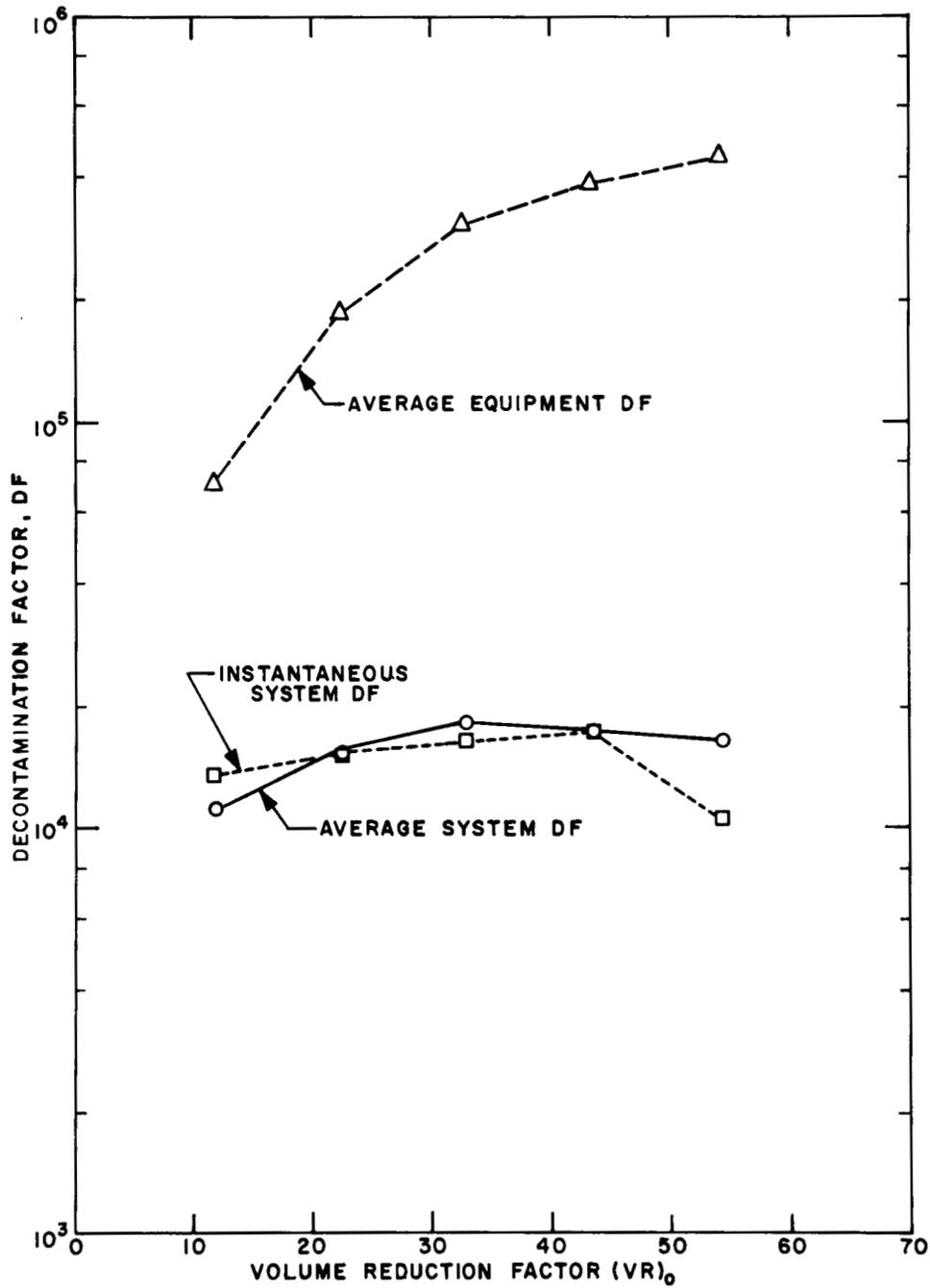


Fig. D-2. Comparison of Average Equipment and System Decontamination Factors for Cesium (^{137}Cs) in a Small-Scale Evaporator. Feed composition is ORNL ILW as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{137}Cs tracer. Evaporator operated in a semicontinuous mode.

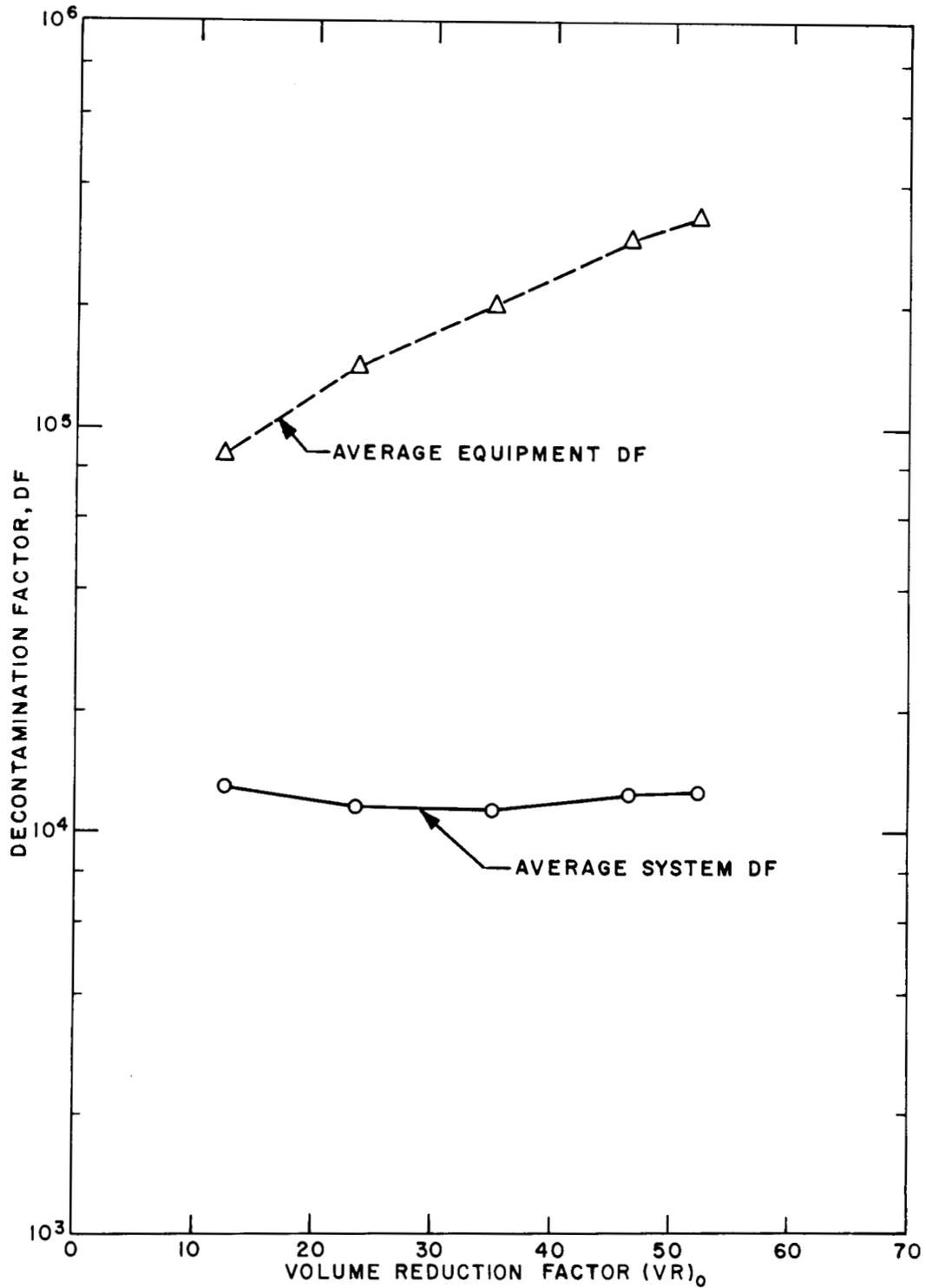


Fig. D-3. Comparison of Average Equipment and System Decontamination Factors for Sodium in a Small-Scale Evaporator. Feed composition is ORNL ILW as given in Table D-1. Evaporator operated in a semicontinuous mode.

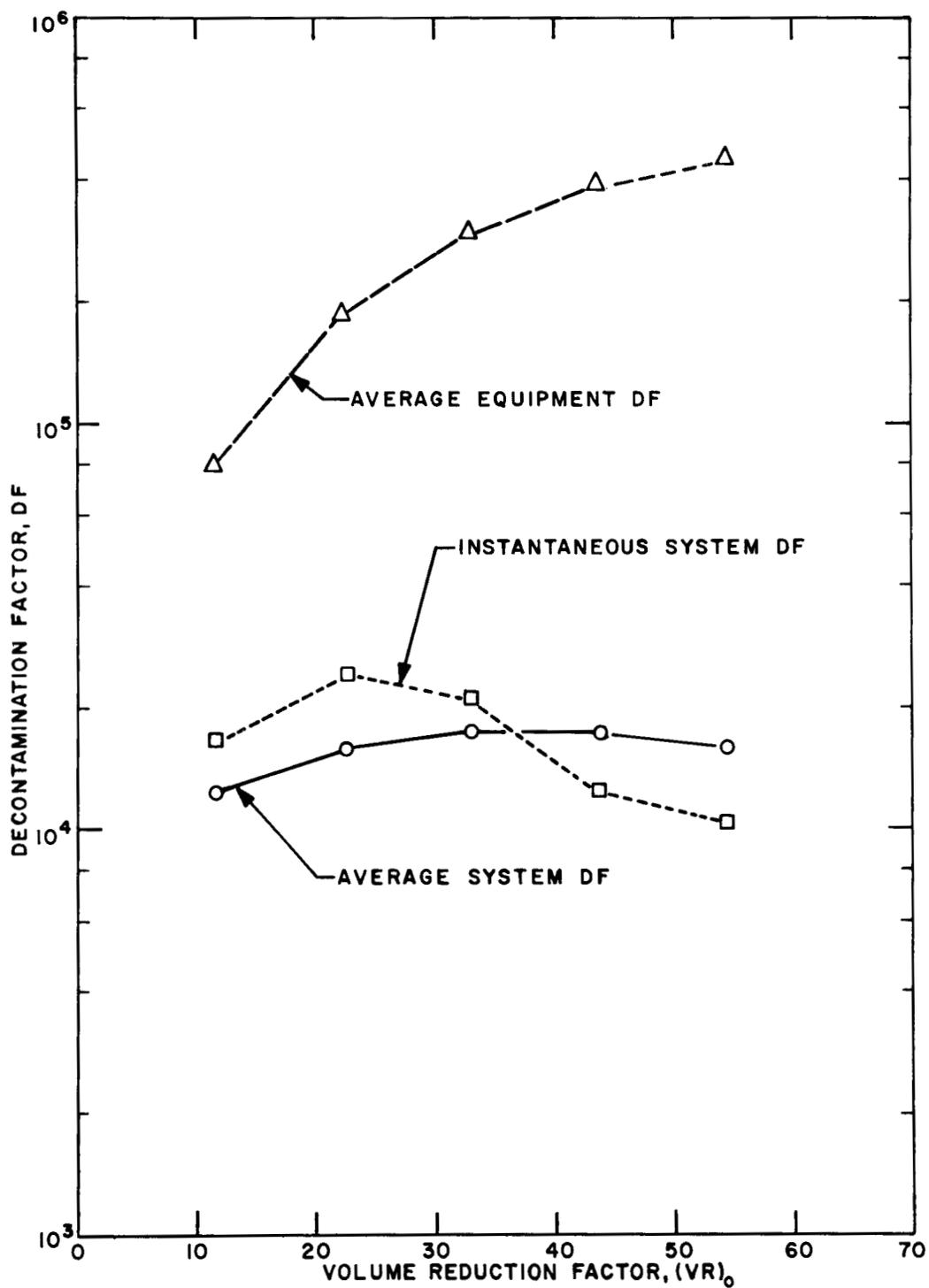


Fig. D-4. Comparison of Average Equipment and System Decontamination Factors for Strontium (^{85}Sr) in a Small-Scale Evaporator. Feed composition is ORNL ILW as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{85}Sr tracer. Evaporator operated in a semicontinuous mode.

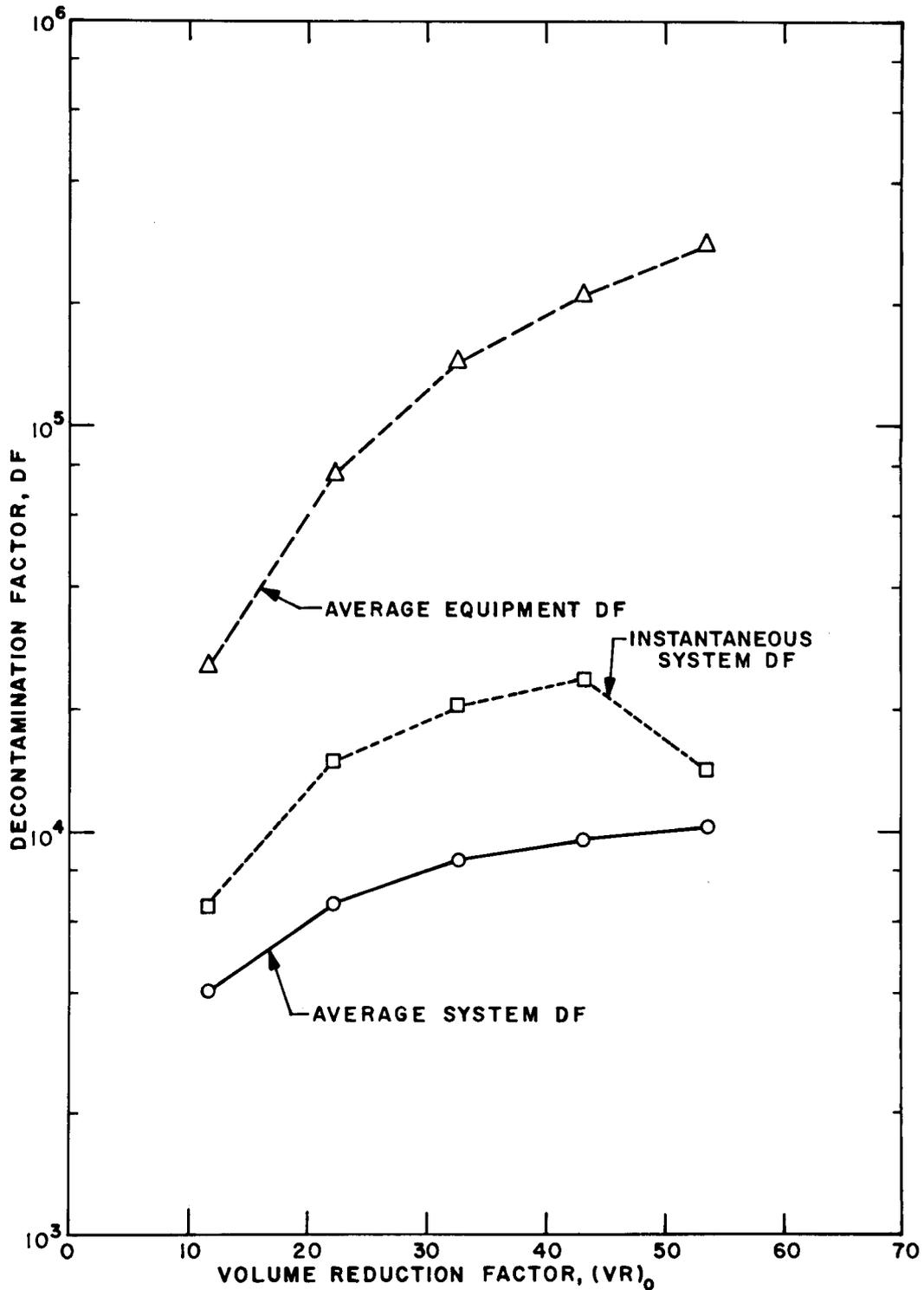


Fig. D-5. Comparison of Average Equipment and System Decontamination Factors for Ruthenium (^{106}Ru) in a Small-Scale Evaporator. Feed composition is ORNL ILW as given in Table D-1 plus $0.4 \mu\text{Ci/ml}$ of ^{106}Ru tracer. Evaporator operated in a semicontinuous mode.

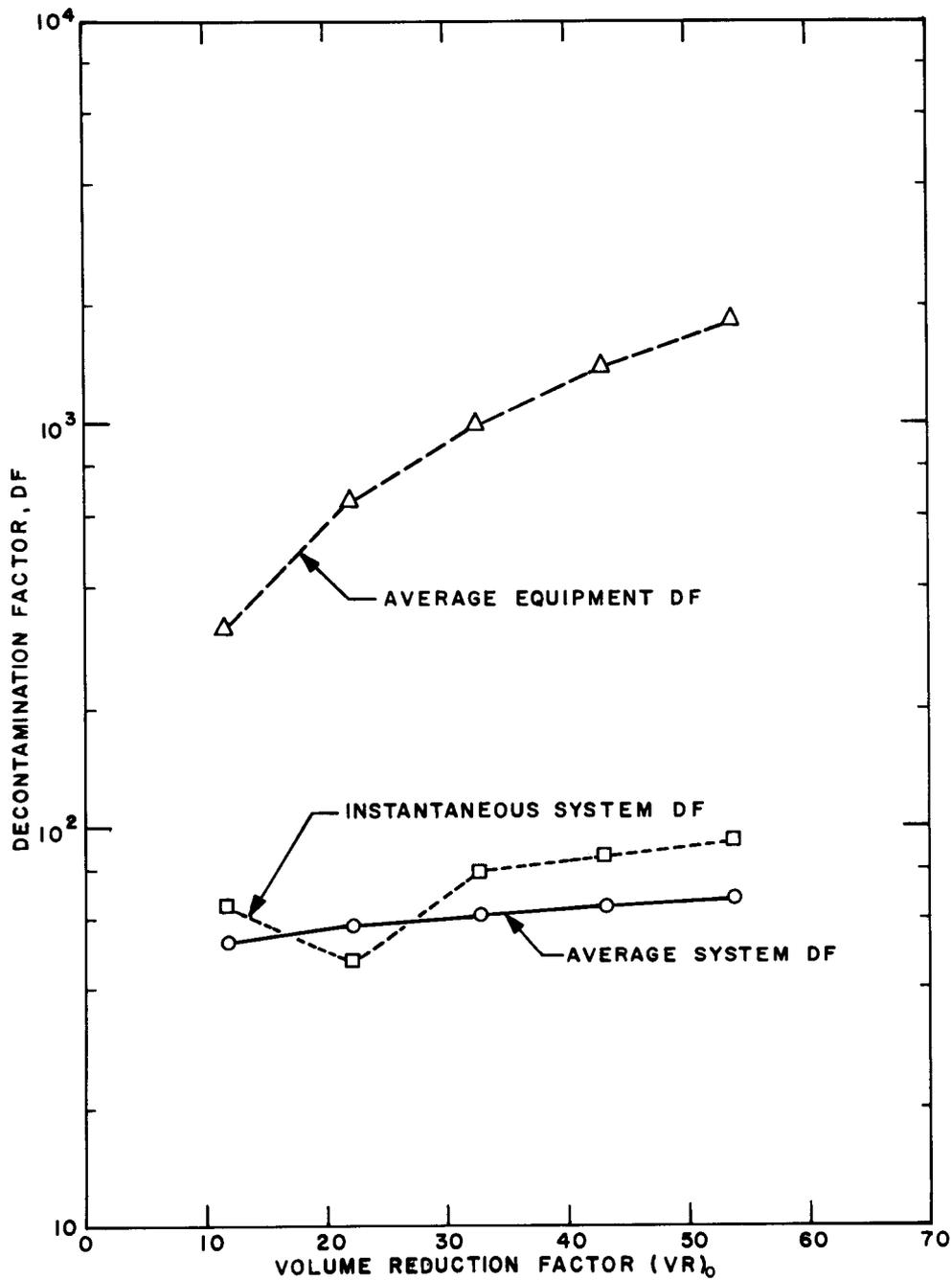


Fig. D-6. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is ORNL IILW as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer. Evaporator operated in a semicontinuous mode.

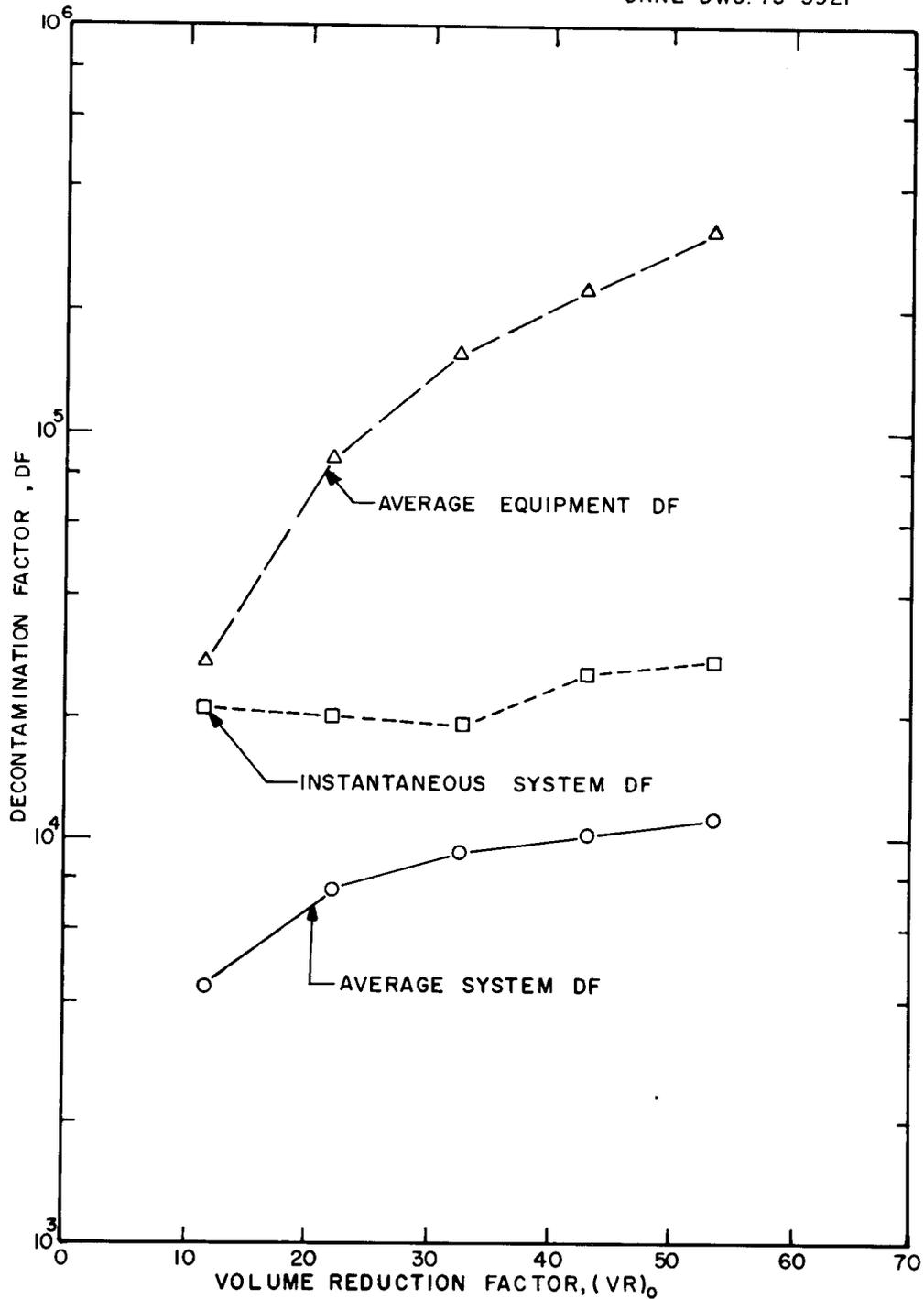


Fig. D-7. Comparison of Average Equipment and System Decontamination Factors for Iodine (¹³¹I) in a Small-Scale Evaporator. Feed composition is ORNL ILW as given in Table D-1 plus 0.2 μCi/ml of ¹³¹I tracer and 0.01 g-mole/liter of KI. Evaporator operated in a semicontinuous mode.

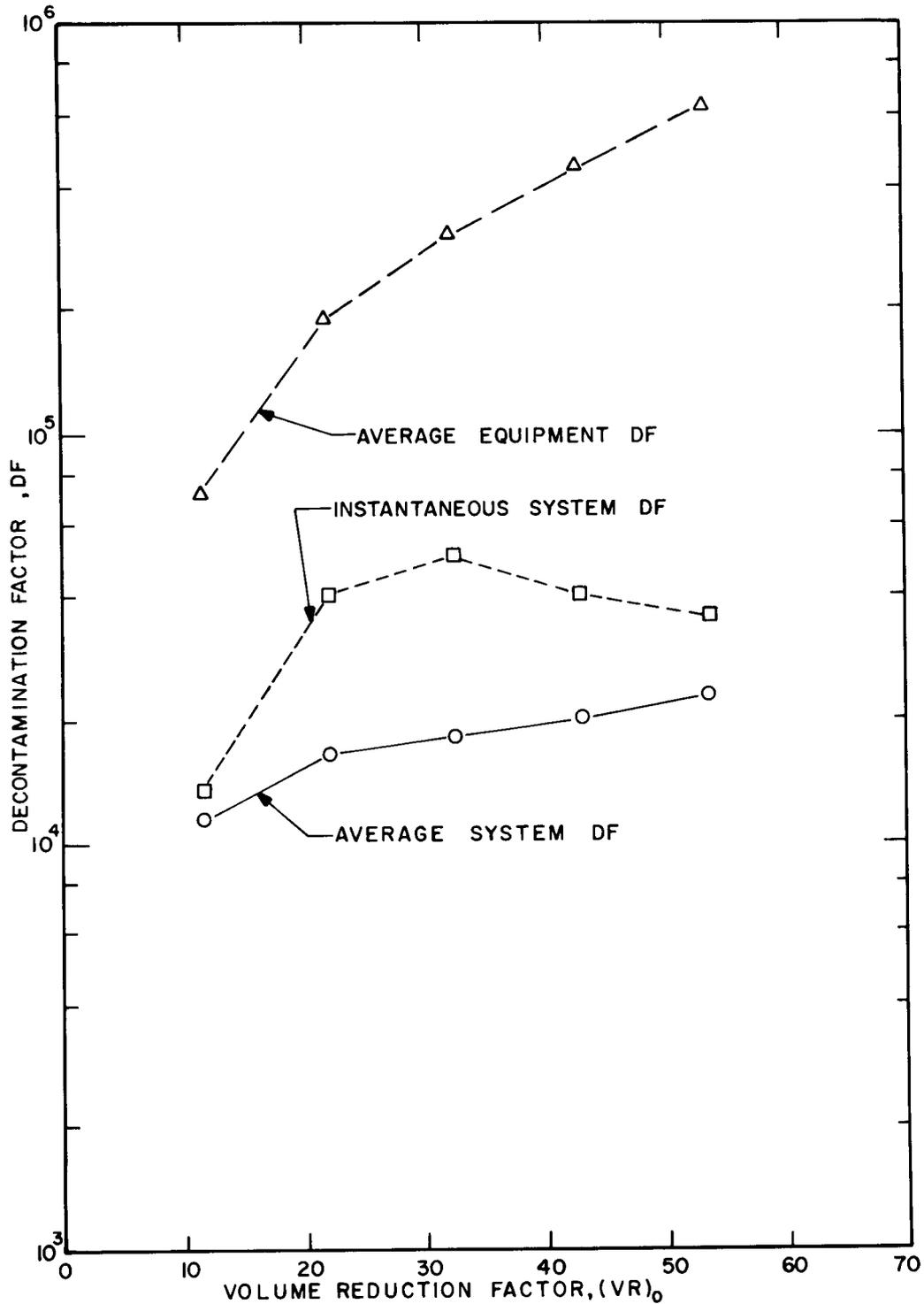


Fig. D-8. Comparison of Average Equipment and System Decontamination Factors for Cesium (^{137}Cs) in a Small-Scale Evaporator. Feed composition is borate waste as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{137}Cs tracer. Evaporator operated in a semicontinuous mode.

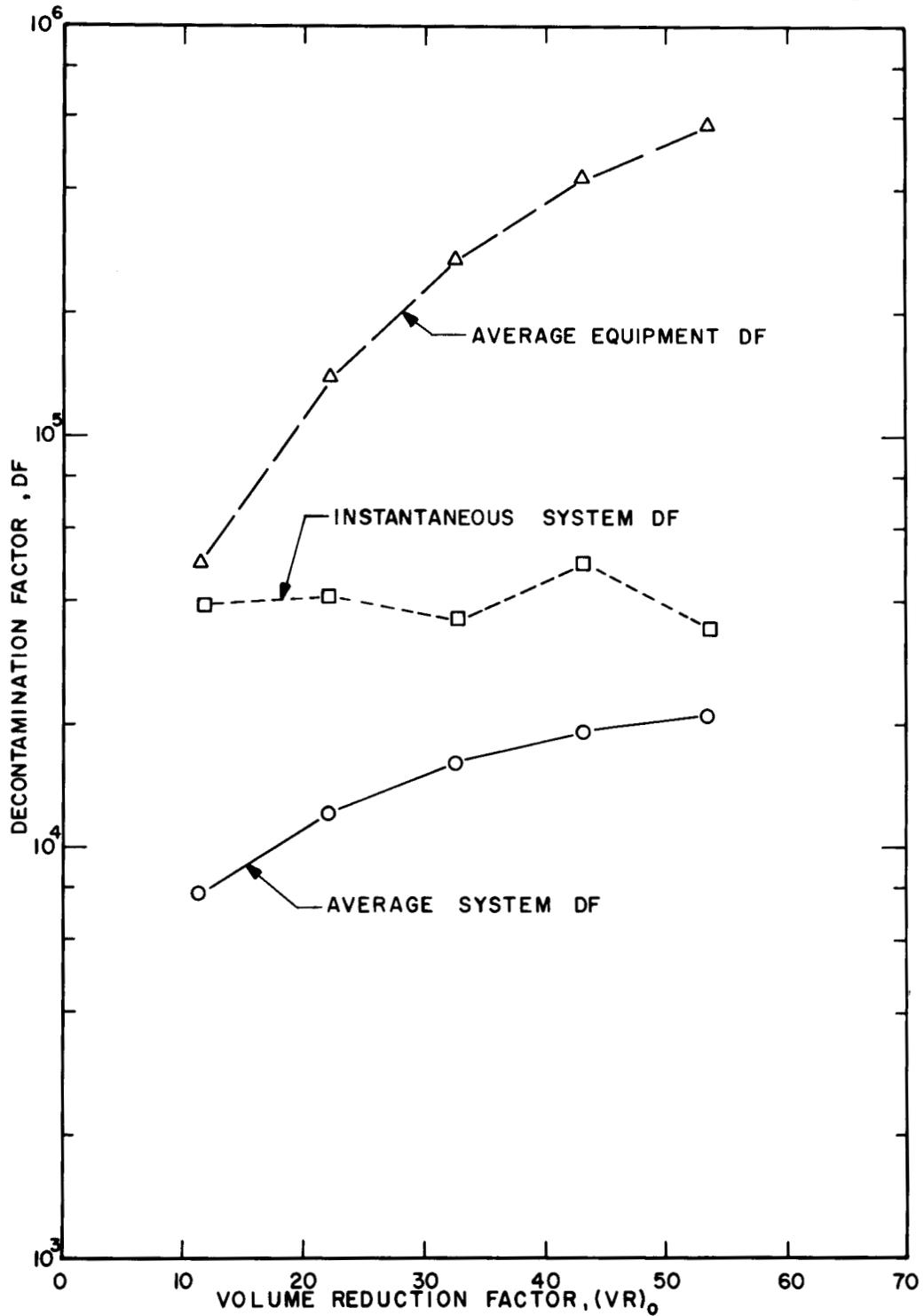


Fig. D-9. Comparison of Average Equipment and System Decontamination Factors for Ruthenium (^{106}Ru) in a Small-Scale Evaporator. Feed composition is borate waste given in Table D-1 plus $0.4 \mu\text{Ci/ml}$ of ^{106}Ru tracer. Evaporator operated in a semicontinuous mode.

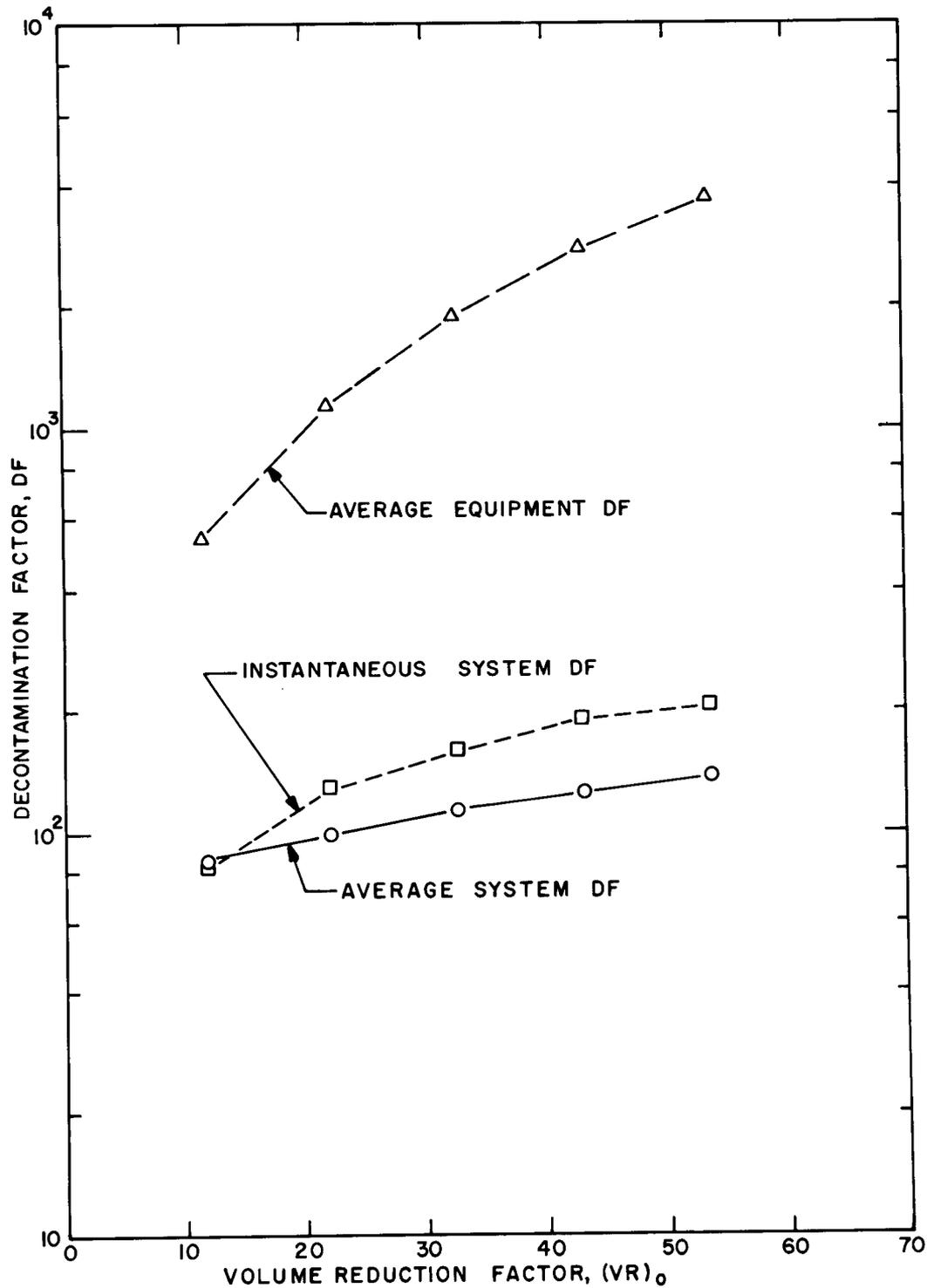


Fig. D-10. Comparison of Average Equipment and System Decontamination Factors for Iodine (¹³¹I) in a Small-Scale Evaporator. Feed composition is borate waste as given in Table D-1 plus 0.2 $\mu\text{Ci/ml}$ of ¹³¹I tracer. Evaporator operated in a semicontinuous mode.

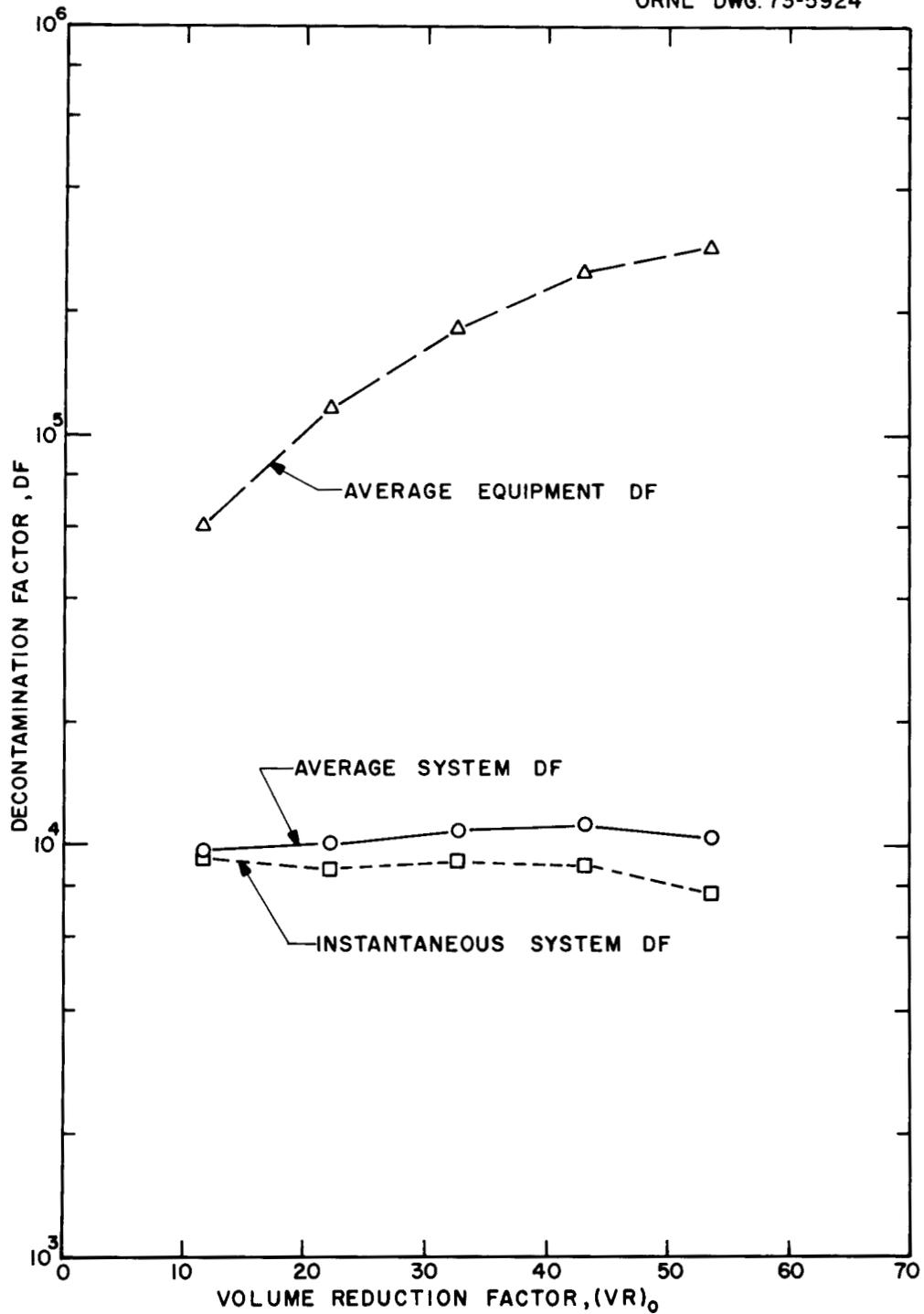


Fig. D-11. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is borate waste as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer and $0.01 \text{ g-mole/liter}$ of KI. Evaporator operated in a semicontinuous mode.

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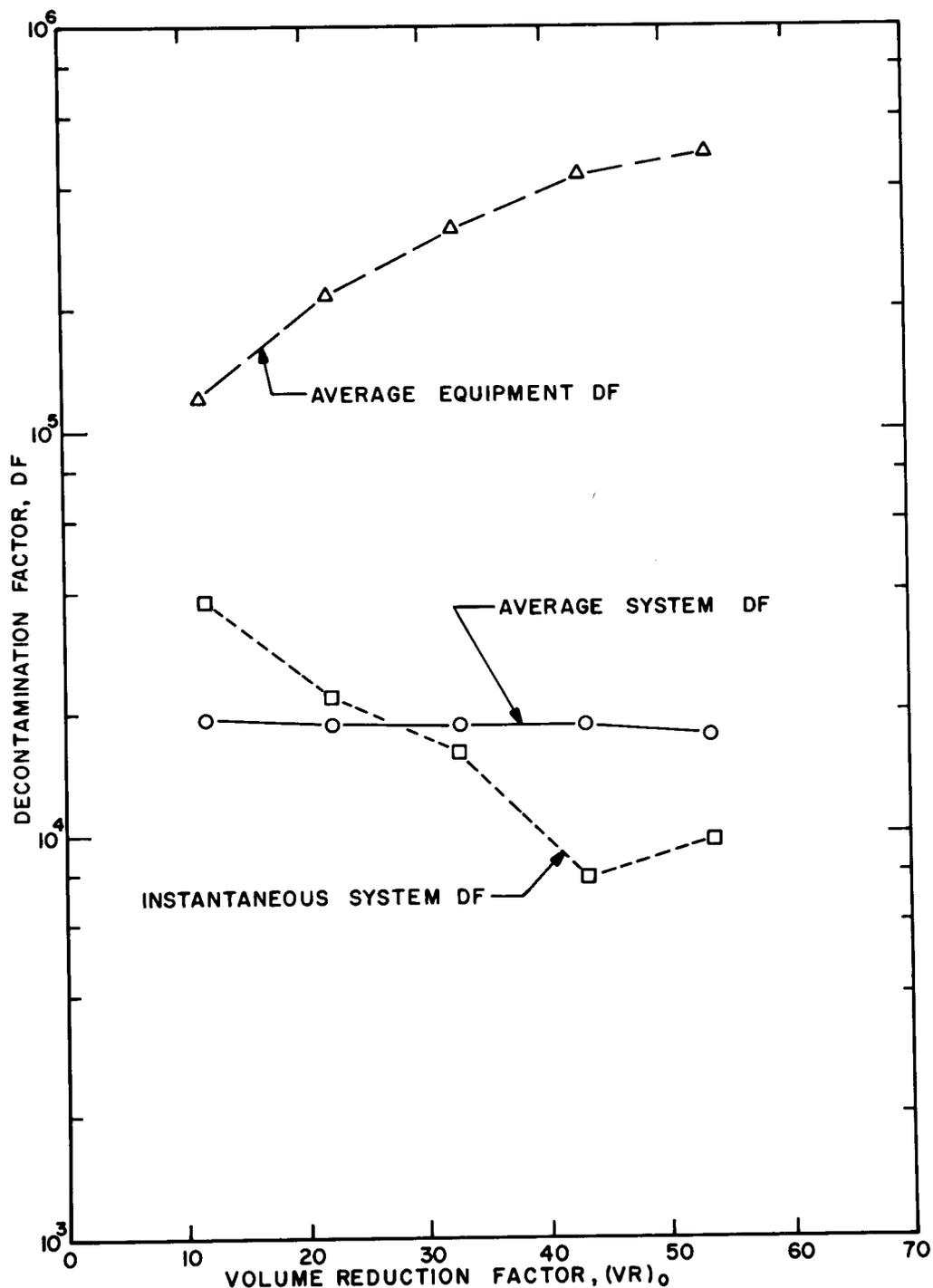


Fig. D-12. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is borate waste as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer and $0.01 \text{ g-mole/liter}$ of KI. Evaporator operated in a semicontinuous mode.

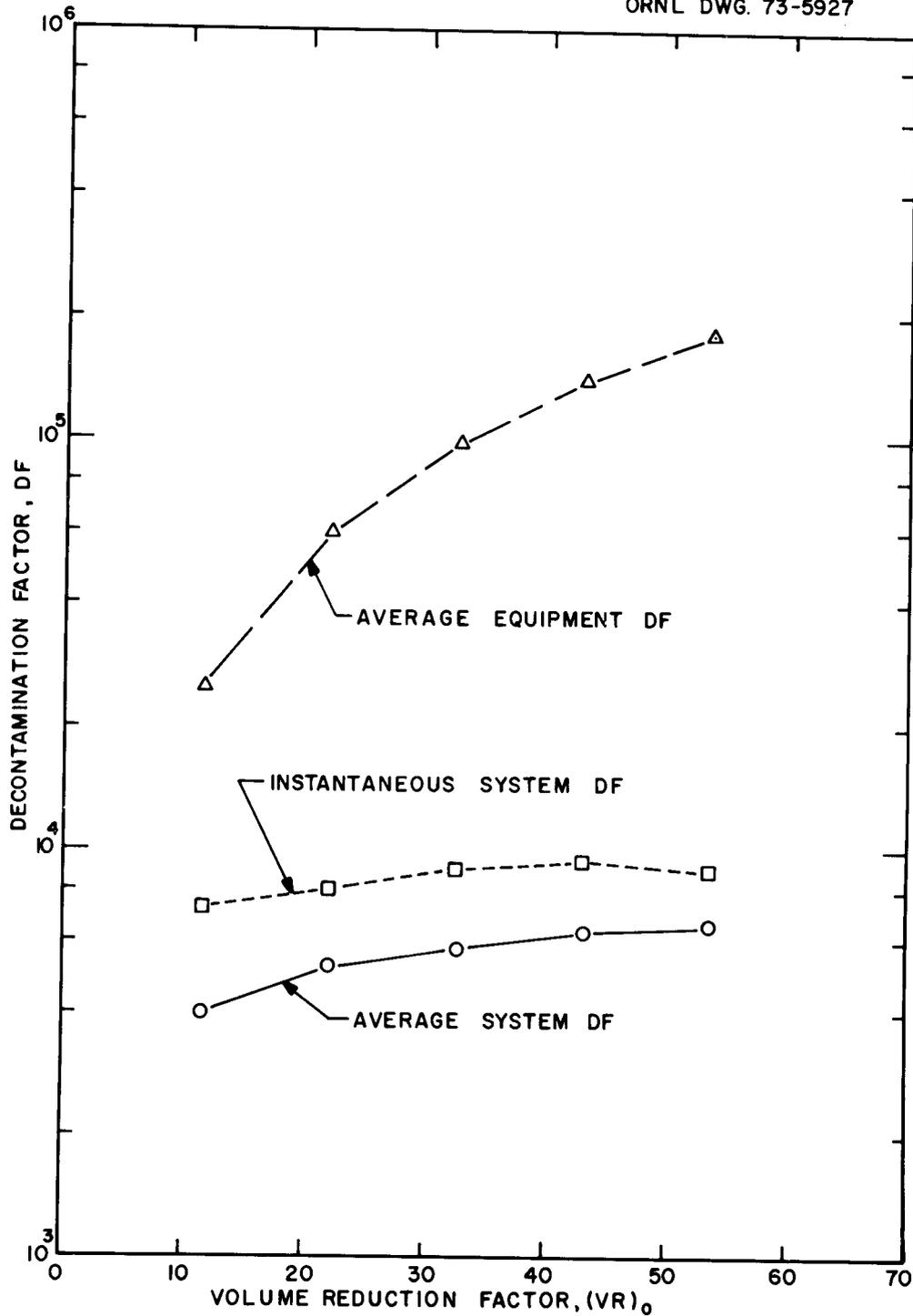


Fig. D-13. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is borate waste as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer, $0.01 \text{ g-mole/liter}$ of KI, and 0.5 g/liter of diethylbenzene. Evaporator operated in a semicontinuous mode.

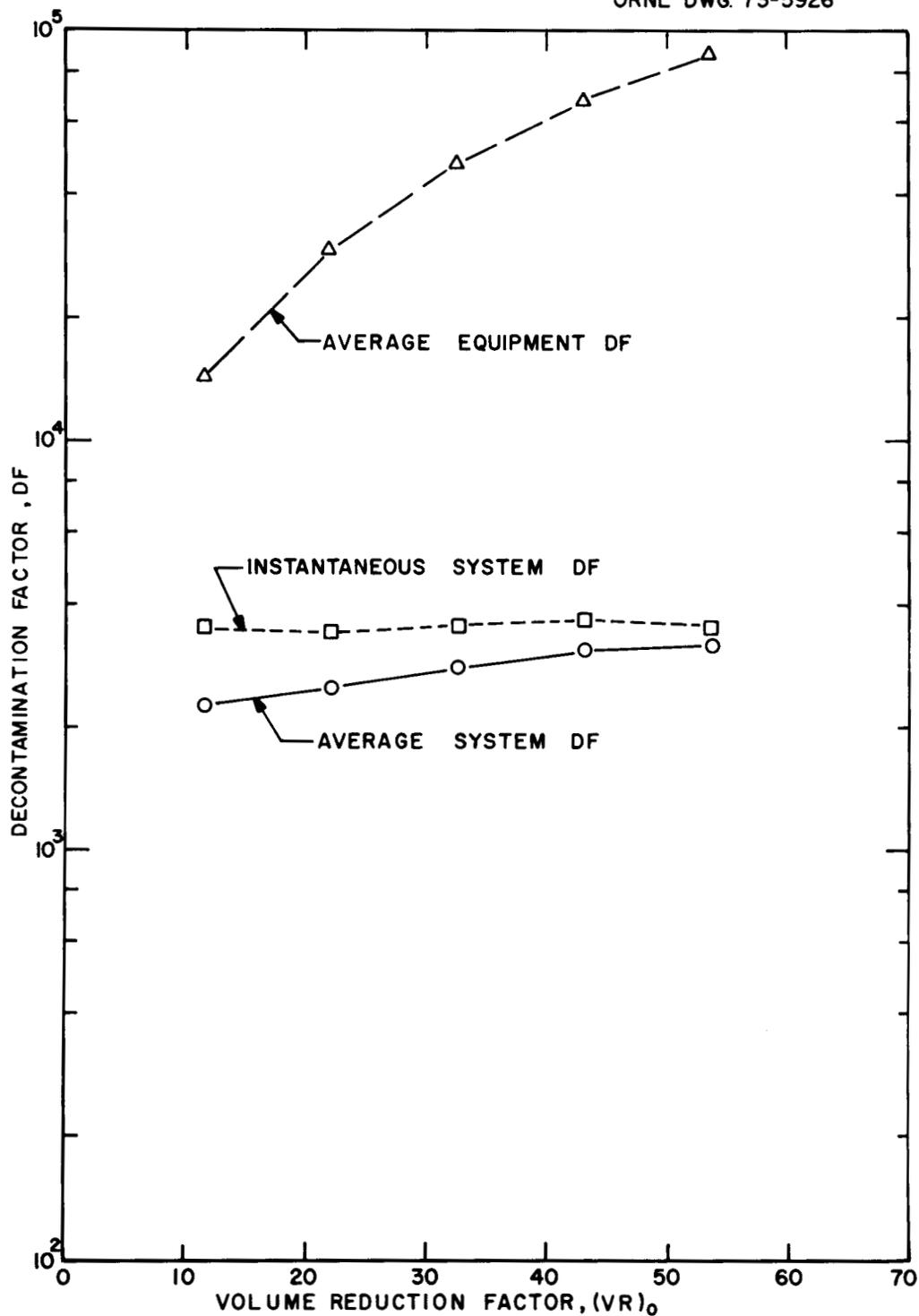


Fig. D-14. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is borate waste as given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer, $0.01 \text{ g-mole/liter}$ of KI, and 0.5 g/liter of diethylbenzene. Evaporator operated in a semicontinuous mode.

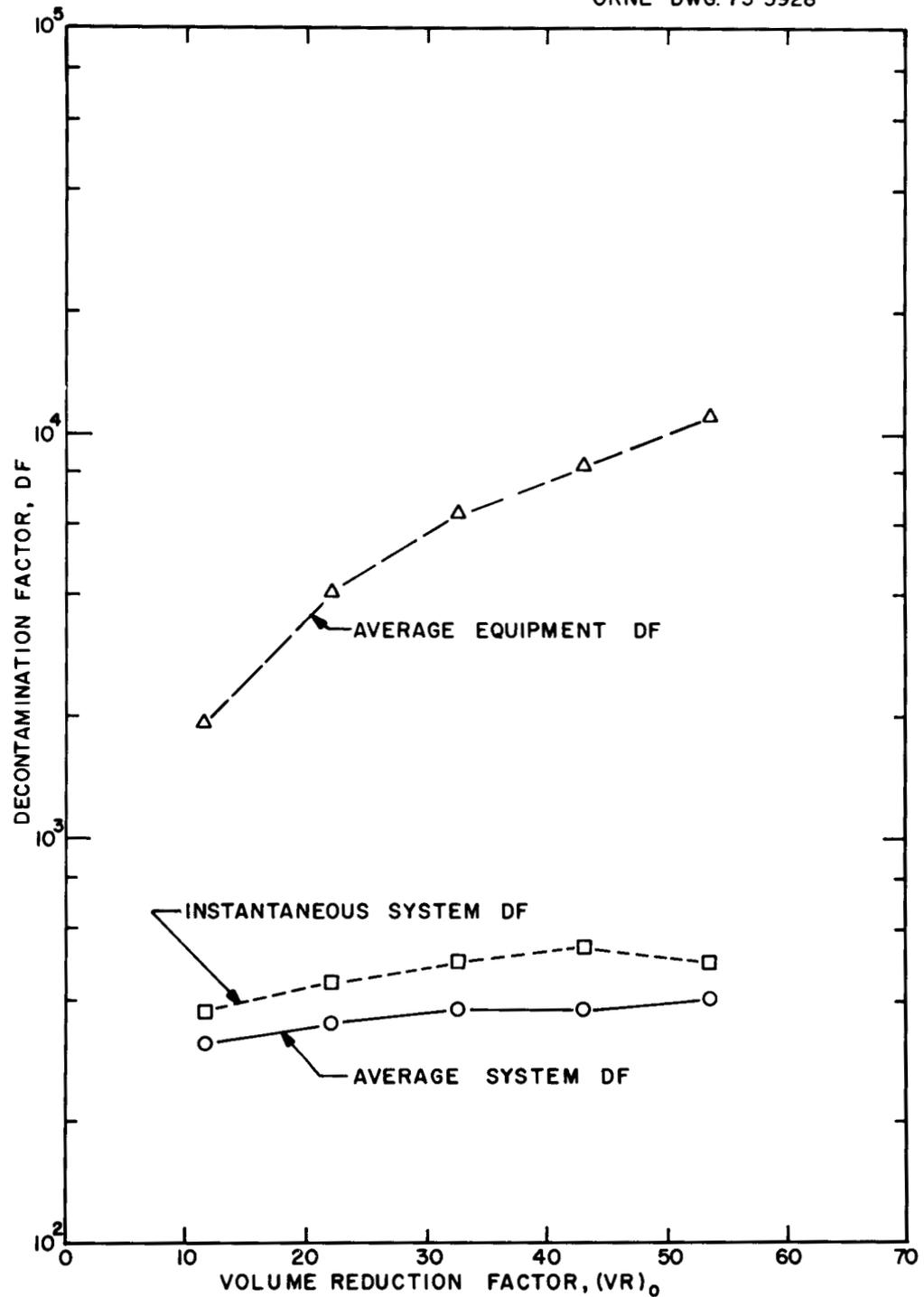


Fig. D-15. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is borate waste given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer, $0.02 \text{ g-mole/liter}$ of KI, and 0.5 g/liter of diethylbenzene. Evaporator operated in a semicontinuous mode.

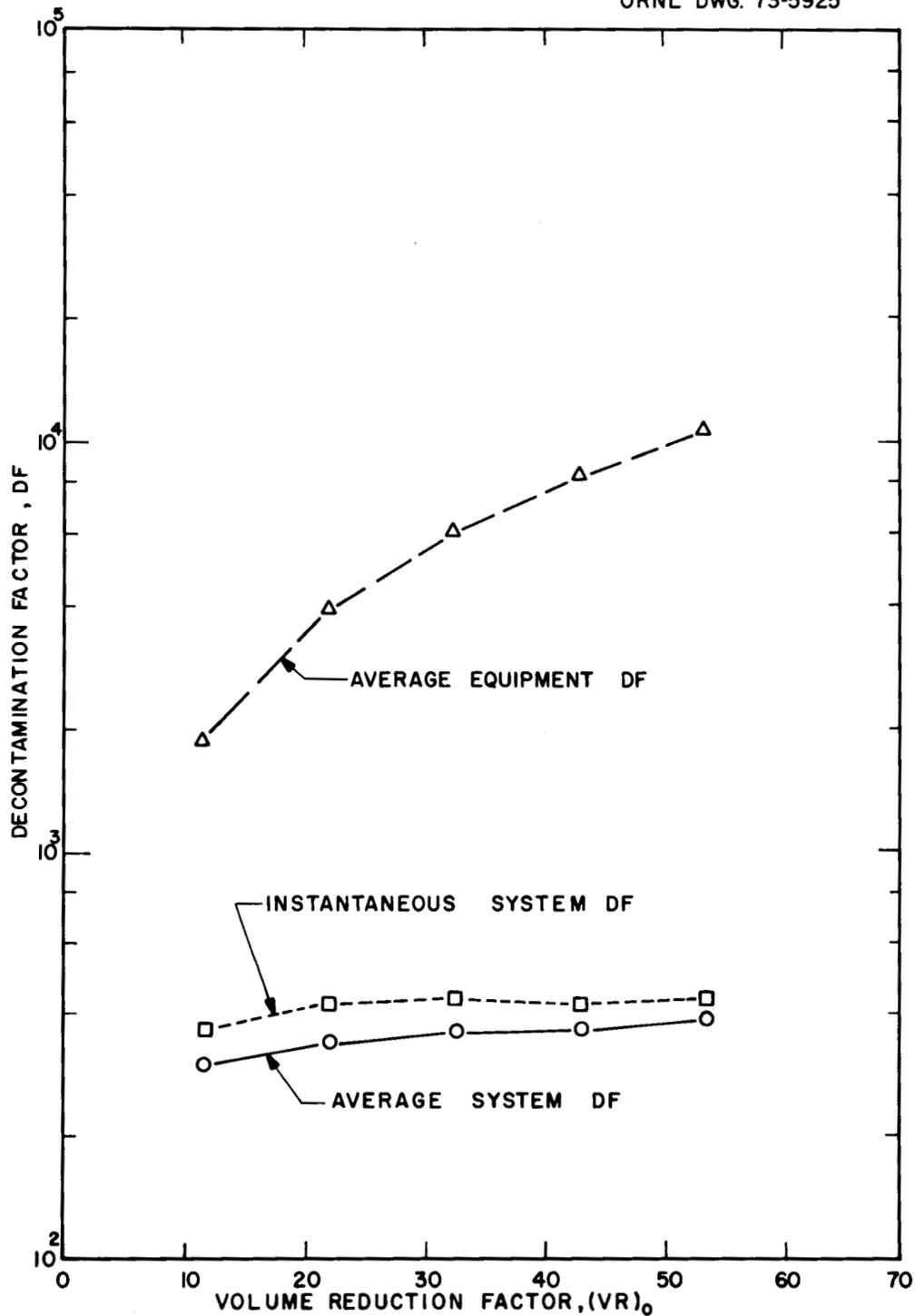


Fig. D-16. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is borate waste given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer, $0.02 \text{ g-mole/liter}$ of KI, and 0.5 g/liter of diethylbenzene. Evaporator operated in a semicontinuous mode.

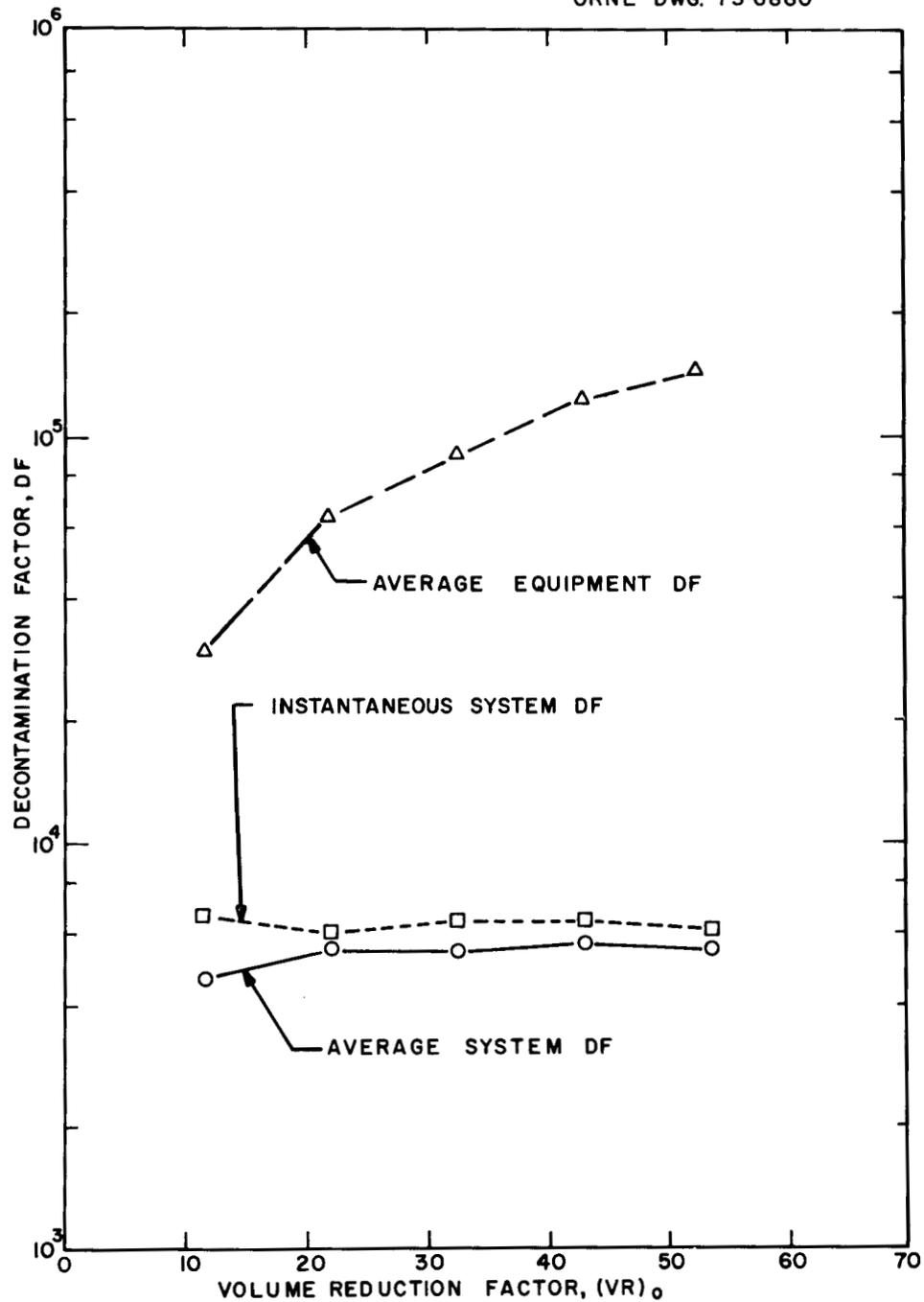


Fig. D-17. Comparison of Average Equipment and System Decontamination Factors for Iodine (^{131}I) in a Small-Scale Evaporator. Feed composition is borate waste given in Table D-1 plus $0.2 \mu\text{Ci/ml}$ of ^{131}I tracer, $0.02 \text{ g-mole/liter}$ of KI, 0.5 g/liter of diethylbenzene, and 0.1 g-mole/liter of sodium sulfite (Na_2SO_3). Evaporator operated in a semicontinuous mode.

APPENDIX E. RESULTS OF PERFORMANCE TEST ON THE
H. B. ROBINSON UNIT NO. 2 WASTE EVAPORATOR

Table E-1. Results of a Performance Test^a on the Waste Evaporator at H. B. Robinson Unit No. 2 After Modification

Date	April 13, 1972								April 14, 1972			
	1000	1200	1400	1600	1800	2000	2200	2400	0200	0400	0600	1000
Sodium												
Feed (ppm)	2933	4633	5660	4025	4127	3233	3163	4051	5027	4134	3438	3374 ^c
Condensate (ppm)	3.22	0.10	0.18	0.32	0.02	0.02	0.03	0.02	0.11	0.12	0.06	0.15 ^c
(DF) _s ^b	9.10 x 10 ²	4.68 x 10 ⁴	3.14 x 10 ⁴	1.26 x 10 ⁴	2.06 x 10 ⁵	1.61 x 10 ⁵	1.05 x 10 ⁵	2.03 x 10 ⁵	4.57 x 10 ⁴	3.45 x 10 ⁴	5.73 x 10 ⁴	5.58 x 10 ^{4c}
Boron												
Feed (ppm)	250	477	892	946	1114	1125	1223	1545	2250	2128	1988	2086 ^c
Condensate (ppm)	0.2	0.4	0.5	<0.1	0.2	<0.1	0.3	<0.1	<0.1	0.6	0.5	0.5 ^c
(DF) _s ^b	1.25 x 10 ³	1.19 x 10 ³	1.78 x 10 ³	>9.46 x 10 ³	5.57 x 10 ³	>1.12 x 10 ⁴	4.07 x 10 ³	>1.55 x 10 ⁴	>2.25 x 10 ⁴	3.55 x 10 ³	3.98 x 10 ³	1.02 x 10 ^{3c}
⁵⁴ Mn												
Feed (μCi/ml)	1.11 x 10 ⁻⁵	--	--	3.24 x 10 ⁻⁵	--	--	--	6.50 x 10 ⁻⁵	1.11 x 10 ^{-5c}	--	8.78 x 10 ⁻⁵	2.27 x 10 ⁻⁴
Condensate (μCi/ml)	<3.0 x 10 ⁻⁸	--	--	<3.0 x 10 ⁻⁸	--	--	--	<3.0 x 10 ⁻⁸	<3.0 x 10 ^{-8c}	--	<4.0 x 10 ⁻⁸	<3.0 x 10 ⁻⁸
(DF) _s ^b	>3.7 x 10 ²	--	--	>1.08 x 10 ³	--	--	--	>2.13 x 10 ³	>3.04 x 10 ^{3c}	--	>2.19 x 10 ³	>7.57 x 10 ³
⁵⁸ Co												
Feed (μCi/ml)	2.54 x 10 ⁻⁵	--	--	9.76 x 10 ⁻⁵	--	--	--	1.64 x 10 ⁻⁴	2.24 x 10 ⁻⁴	--	2.09 x 10 ⁻⁴	5.13 x 10 ⁻⁴
Condensate (μCi/ml)	4.53 x 10 ⁻⁷	--	--	3.1 x 10 ⁻⁸	--	--	--	<3.0 x 10 ⁻⁸	<3.0 x 10 ⁻⁸	--	<4.0 x 10 ⁻⁸	7.6 x 10 ⁻⁸
(DF) _s ^b	5.6 x 10 ¹	--	--	3.14 x 10 ³	--	--	--	>5.47 x 10 ³	>7.46 x 10 ³	--	>5.22 x 10 ³	6.75 x 10 ³
⁶⁰ Co												
Feed (μCi/ml)	4.92 x 10 ⁻⁵	--	--	1.18 x 10 ⁻⁴	--	--	--	1.97 x 10 ⁻⁴	2.85 x 10 ⁻⁴	--	2.55 x 10 ⁻⁴	6.43 x 10 ⁻⁴
Condensate (μCi/ml)	1.46 x 10 ⁻⁶	--	--	8.73 x 10 ⁻⁸	--	--	--	<3.0 x 10 ⁻⁸	<3.0 x 10 ⁻⁸	--	<6.0 x 10 ⁻⁸	2.82 x 10 ⁻⁷
(DF) _s ^b	3.37 x 10 ¹	--	--	1.35 x 10 ³	--	--	--	>6.56 x 10 ³	>9.5 x 10 ³	--	>4.25 x 10 ³	2.28 x 10 ³
pH												
Feed	12.9	12.9	13.0	13.0	13.0	12.7	11.7	10.75	10.6	10.2	9.9	10.0
Condensate	5.7	7.1	7.1	7.3	7.8	7.8	7.7	7.3	7.0	6.9	6.6	4.5
Gross β												
Feed (μCi/ml)	1.86 x 10 ⁻⁵	7.57 x 10 ⁻⁵	1.20 x 10 ⁻⁴	1.25 x 10 ⁻⁴	1.42 x 10 ⁻⁴	1.19 x 10 ⁻⁴	1.45 x 10 ⁻⁴	1.88 x 10 ⁻⁴	2.53 x 10 ⁻⁴	2.42 x 10 ⁻⁴	2.50 x 10 ⁻⁴	4.04 x 10 ⁻⁴
Condensate (μCi/ml)	--	1.10 x 10 ⁻⁷	5.58 x 10 ⁻⁸	--	2.56 x 10 ⁻⁸	1.12 x 10 ⁻⁸	6.20 x 10 ⁻⁹	4.22 x 10 ⁻⁸	<1.7 x 10 ⁻⁸	5.21 x 10 ⁻⁸	1.36 x 10 ⁻⁸	2.50 x 10 ⁻⁷
(DF) _s ^b	--	6.88 x 10 ²	2.15 x 10 ³	--	5.54 x 10 ³	1.06 x 10 ⁴	2.33 x 10 ⁴	4.45 x 10 ³	>1.4 x 10 ⁴	4.64 x 10 ³	1.84 x 10 ⁴	1.62 x 10 ³

^aFrom ref. 21.^bRatio of feed to condensate concentration.^cInconsistent sets of numbers (as given in ref. 21).

APPENDIX F. EVAPORATOR AT TEST AREA NORTH (TAN)

The Test Area North (at the National Reactor Testing Station, Idaho) includes several nuclear test facilities and provides various fabrication, decontamination, and hot-shop services to the station. The Technical Services Facility (TSF) is the center of this test area and contains several large machine shops, laboratories, hot cells, a large shielded hot shop, as well as decontamination facilities. Nuclear test facilities located around the TSF include the Initial Engineering Test Facility (IET), Field Engineering Test Facility (FET), Low Power Test Facility (LPT), and Experimental Beryllium Oxide Reactor Facility (EBOR).

All potentially radioactive liquid wastes generated at TAN are accumulated in three 10,000-gal collection tanks and are concentrated in an evaporator (Fig. F-1). These liquids amount to about 15,000 gal annually and include waste from laboratory sinks, cell and shop floor drains, equipment decontamination, and fuel storage pool. Representative analyses of liquid waste in the collection tanks are given in Table F-1. The evaporator is a 1,000-gal, steam-jacketed kettle. No internal entrainment separators such as baffles or wire mesh are in the evaporator; however, vapors from the evaporator pass through a cyclone separator. The design capacity of the evaporator is about 100 gal/hr.

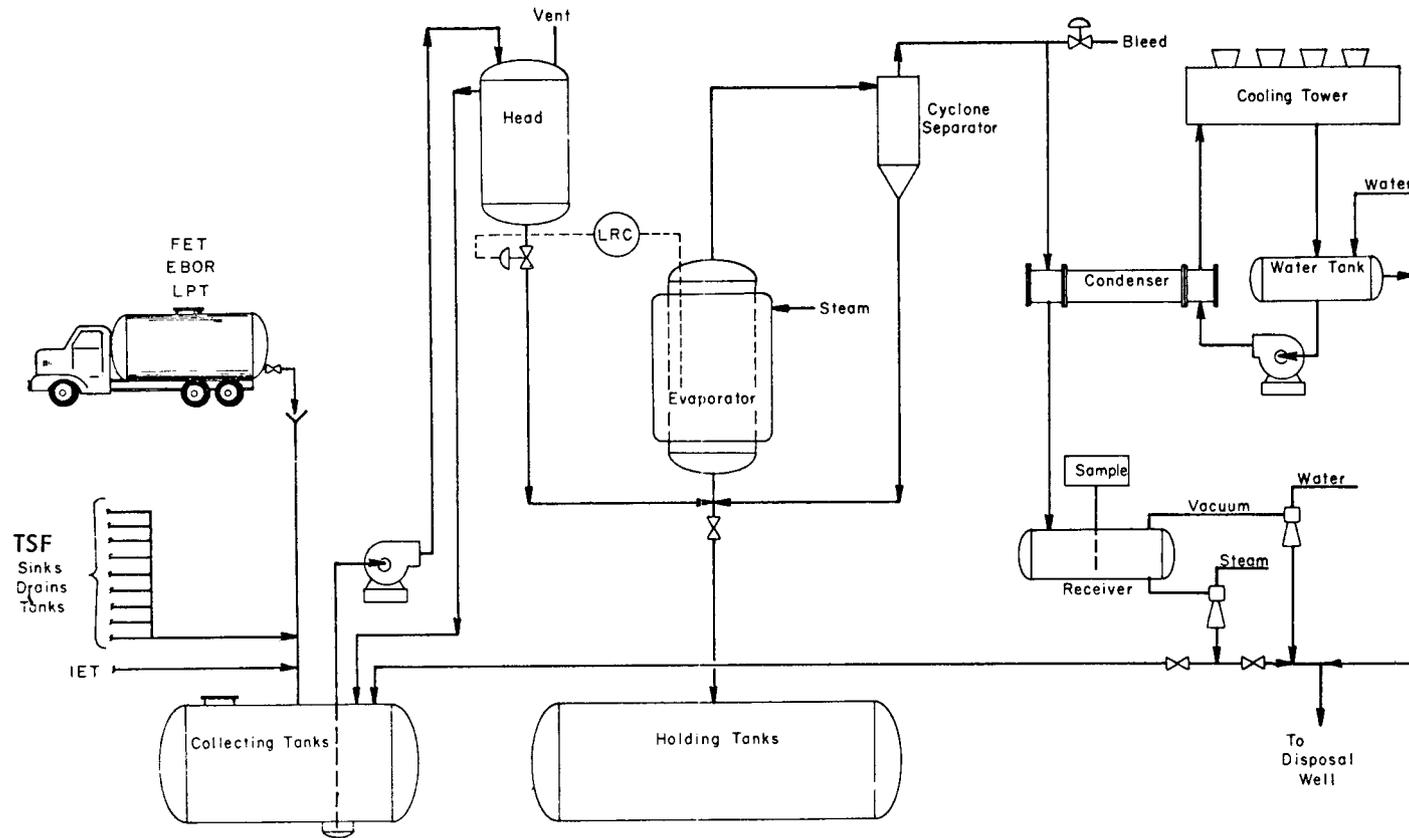


Fig. F-1. Flowsheet for Test Area North (National Reactor Testing Station) Radwaste. FET = Field Engineering Test Facility; EBOR = Experimental Beryllium Oxide Reactor Facility; LPT = Low Power Test Facility; IET = Initial Engineering Test Facility; TSF = Technical Services Facility.

Table F-1. Representative Analyses of Liquid Radwaste at Test Area North

pH	7.51	7.57	7.54
Specific Gravity	1.000	1.002	1.000
Total Dissolved Solids	0.076 g/liter	0.058 g/liter	0.069 g/liter
Sulfate	0.20 g/liter	0.018 g/liter	0.020 g/liter
Phosphate	<0.2 mg/liter	<0.2 mg/liter	0.28 ±0.18 mg/liter
Nitrate	0.82 mg/liter	<0.6 mg/liter	1.36 mg/liter
Free Halide (Cl ⁻ , Br ⁻)	550 ppm	805 ppm	1215 ppm
α	0.2 d/s/ml	0.3 d/s/ml	0.3 d/s/ml
β	7.05 x 10 ³ d/s/ml	1.18 x 10 ⁴ d/s/ml	1.46 x 10 ⁴ d/s/ml
γ-Scan			
Co-60	4.35 x 10 ² d/s/ml	7.97 x 10 ² d/s/ml	6.82 x 10 ² d/s/ml
Cs-134	7.95 x 10 ² d/s/ml	2.38 x 10 ² d/s/ml	3.78 x 10 ² d/s/ml
Cs-137	5.76 x 10 ³ d/s/ml	7.86 x 10 ³ d/s/ml	1.44 x 10 ⁴ d/s/ml
Mn-54	<1.10 x 10 ² d/s/ml	3.30 x 10 ² d/s/ml	<2.62 x 10 ² d/s/ml
Emission Spectrograph			
Major ≤ 5%	Sodium	Sodium	Sodium

APPENDIX G. EVAPORATOR AT IDAHO CHEMICAL PROCESSING PLANT (ICPP)

The Idaho Chemical Processing Plant (at the National Reactor Testing Station, Idaho) is one of four plants owned and administered by the AEC for the primary purpose of recovering uranium from spent fuel. A secondary but important purpose of these AEC facilities is the development of improved fuel reprocessing methods. During fuel reprocessing, high- and intermediate-level radioactive wastes containing greater than 99% of the fission products, and low-level waste containing less than 1% of the fission products are generated. The high-level wastes are stored for an interim period and then converted to a solid in the Waste Calcining Facility (WCF).

All potentially radioactive liquid wastes generated at ICPP, except high-level wastes, are routed to an evaporator waste collection tank (Fig. G-1). These liquids amount to about 1,200,000 gal annually²⁴ and include waste from laboratory sinks process sampler drains, cell floor drains, equipment decontamination, and some wastes from the test reactor areas at the National Reactor Testing Station (NRTS). These wastes are mainly water containing low concentrations of sodium, potassium, aluminum, permanganate, carbonate, hydroxide, and nitrate, as well as traces of other chemicals occasionally. The solutions are usually acidic but may be basic with concentrations up to 1 M acid or base. A diagram of the evaporator and associated equipment is given in Fig. G-2. The evaporator has an external heat exchanger with vertical tubes and natural circulation (thermosiphon). The flash chamber has an impingement plate and the vapors from the flash chamber pass into an entrainment-separator column containing four bubble-cap trays (Fig. G-2). The design capacity of the evaporator is 500 gal/hr. It is operated in a semicontinuous mode, and a system decontamination factor of 10^4 to mid 10^4 is usually achieved. The results of an operating test are shown in Table G-1.

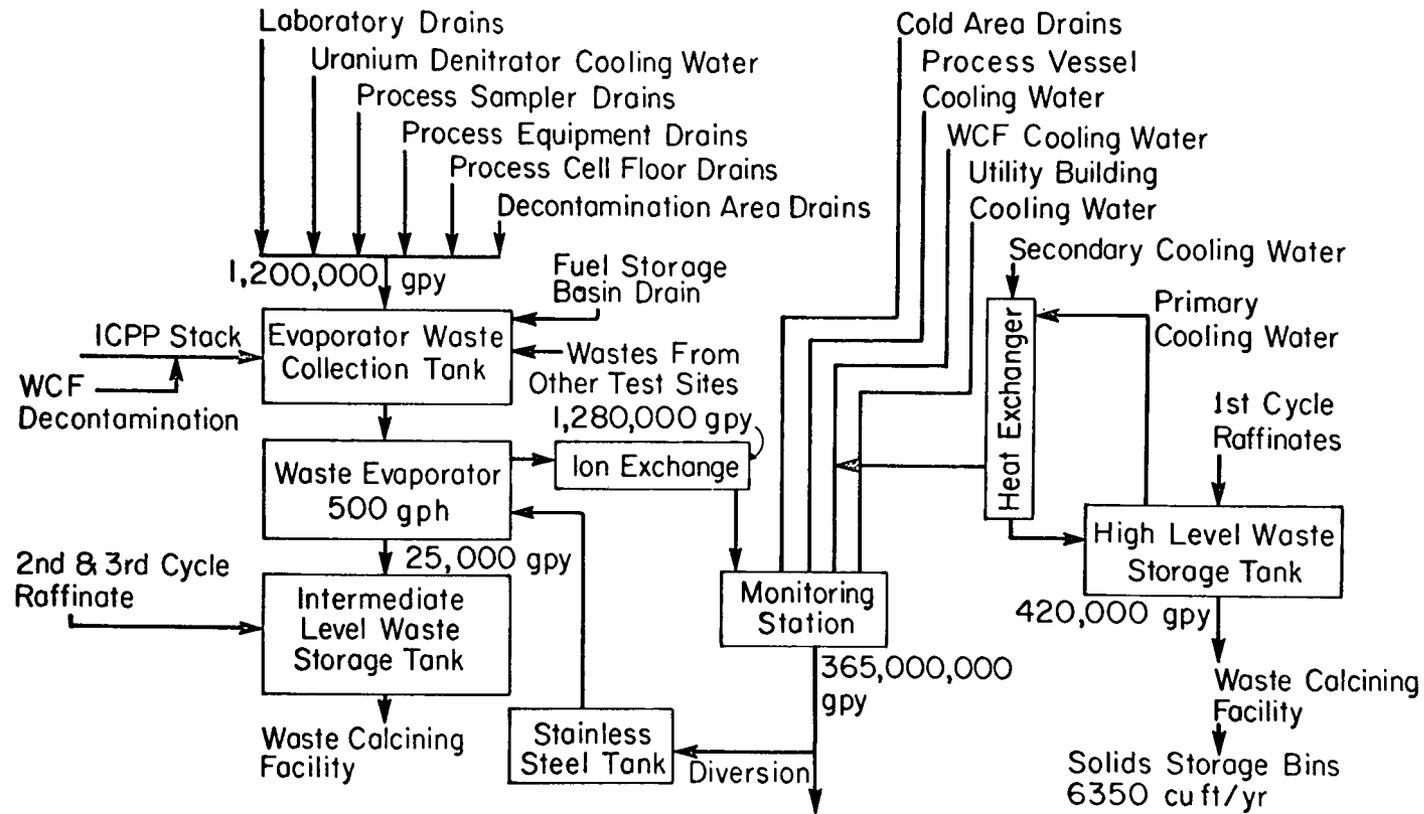


Fig. G-1. Radwaste Collection System at the Idaho Chemical Processing Plant. (From ref. 24)

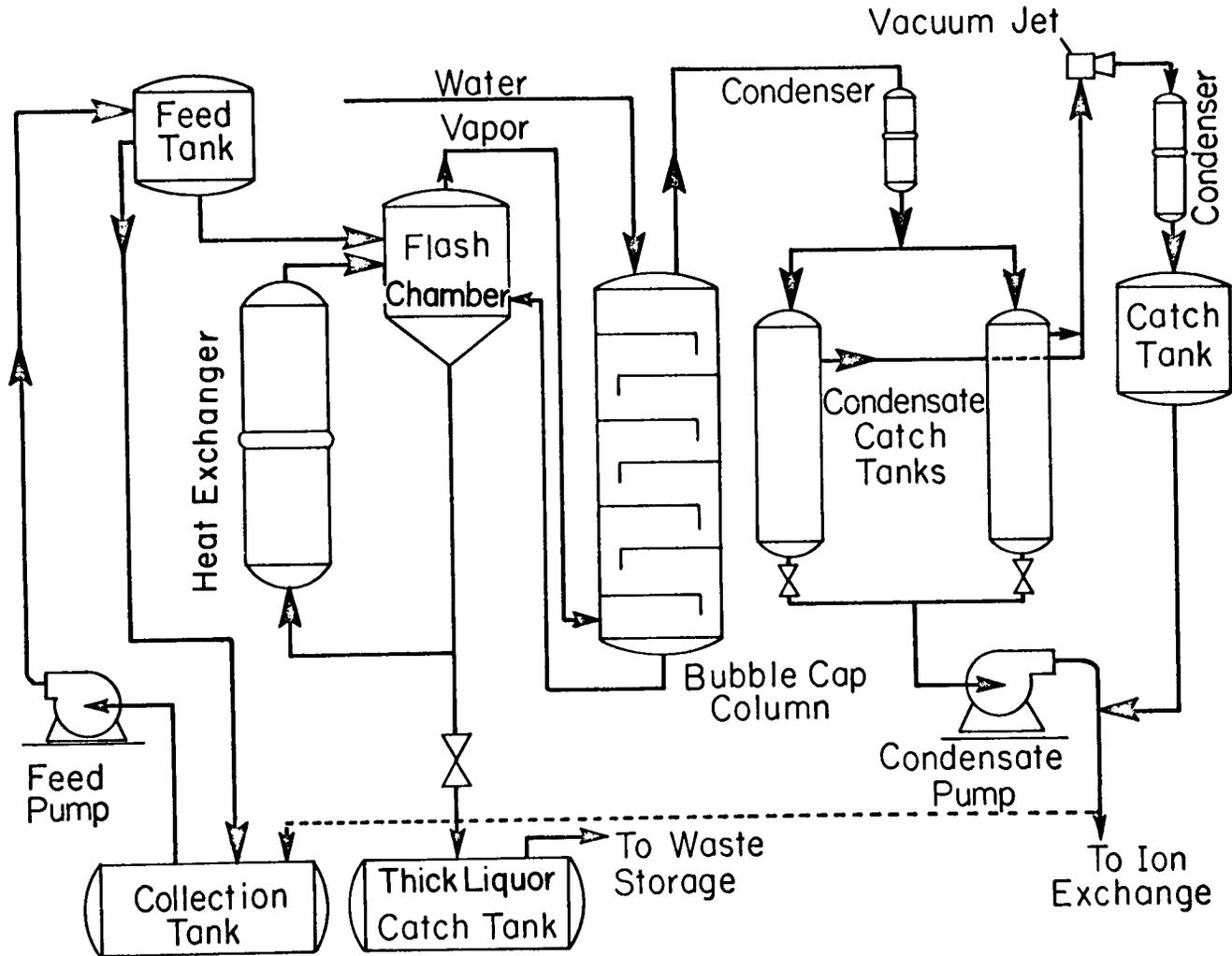


Fig. G-2. Waste Evaporator and Associated Equipment at the Idaho Chemical Reprocessing Plant. (Redrawn from ref. 24)

Table G-1. Results of an Operating Test^a on the ICPP Evaporator

Measurement	Result
Volume of feed, gallons	14,730
Volume reduction factor ^b	21.2
Gross β activity in feed, $\mu\text{Ci/ml}$	185
Gross β activity in condensate, $\mu\text{Ci/ml}$	3.6×10^{-3}
System decontamination factor ^c	5.4×10^4
Equipment decontamination factor ^d	1×10^6

^aFrom ref. 24.

^bFeed rate divided by thick liquor rate.

^cFeed concentration divided by condensate concentration.

^dThick liquor concentration divided by condensate concentration.

APPENDIX H. EVAPORATOR AT OAK RIDGE NATIONAL LABORATORY (ORNL)

Oak Ridge National Laboratory is a research and development center made up of laboratories, chemical pilot plants, radioisotope production plants, nuclear reactors, and supporting facilities. The central waste system can treat these categories of liquid waste: high-activity waste, containing more than 5 Ci/gal; intermediate-level waste (ILW), containing between 0.001 and 5 Ci/gal; and low-level process waste water, containing less than 0.001 Ci/gal. ILW is treated by evaporation.

Intermediate-level wastes are discharged at a rate of about 8,000 gal/day into any of 21 underground stainless-steel monitoring tanks, each located near a source. The wastes drain or are discharged from hoods, glove boxes, cells, and process vessels in the source buildings. The wastes are neutralized with NaOH in the tanks. At proper intervals the wastes are transferred by pumps and steam jets through stainless-steel pipelines to an underground 170,000-gal concrete surge tank. The radionuclides in these wastes (Table H-1) are mainly ^{137}Cs , ^{134}Cs , ^{125}Sb , ^{106}Ru , $^{95}\text{Zr-Nb}$, ^{90}Sr , ^{60}Co , and traces of rare earths. Sodium nitrate and hydroxide comprise about three-fourths of the nonradioactive chemical content. Aluminum, ammonia, sulfate, carbonate, chloride, and traces of other chemicals make up the balance. The total solids range from several to around 10 g/liter. After a period for decay of short-lived radionuclides, the wastes are pumped in batches through stainless steel pipelines to the waste evaporator feed tank (Fig. H-1).

The waste evaporator is a 600-gal/hr stainless steel, submerged-coil pot type which is operated in a semicontinuous mode. Entrainment separators include an impingement baffle in the flash chamber and a bed of wire mesh between the evaporator and the condenser. The condensate flows through an ion-exchange column and is sent to the process (low-level) waste system. Routine operating results for the evaporator are given in Table H-1 and show average system decontamination factors of low 10^4 to mid 10^6 .

Table H-1. Performance Data for ORNL Intermediate-Level Waste Evaporator

Nuclide	Run 2-3-72			Run 3-16-72			Run 4-27-72			Run 6-27-72		
	Feed ^a ($\mu\text{Ci/ml}$)	Condensate ^b ($\mu\text{Ci/ml}$)	Average System DF ^c	Feed ^a ($\mu\text{Ci/ml}$)	Condensate ^b ($\mu\text{Ci/ml}$)	Average System DF ^c	Feed ^a ($\mu\text{Ci/ml}$)	Condensate ^b ($\mu\text{Ci/ml}$)	Average System DF ^c	Feed ^a ($\mu\text{Ci/ml}$)	Condensate ^b ($\mu\text{Ci/ml}$)	Average System DF ^c
⁶⁰ Co	7.03×10^{-2}	4.39×10^{-7}	1.6×10^5	4.00×10^{-3}	2.19×10^{-7}	1.8×10^4	4.50×10^{-2}	6.26×10^{-8}	7.2×10^5	1.80×10^{-2}	1.11×10^{-6}	1.6×10^4
⁹⁰ Sr	6.85×10^{-1}	2.93×10^{-6}	2.3×10^5	2.60×10^{-1}	7.61×10^{-6}	3.4×10^4	3.87	3.01×10^{-6}	1.3×10^6	6.04×10^{-1}	3.60×10^{-5}	1.7×10^4
⁹⁵ Zr-Nb	$\leq 4 \times 10^{-2}$	9.46×10^{-8}	$\leq 4 \times 10^5$	$\leq 2 \times 10^{-3}$	1.05×10^{-7}	$\leq 2 \times 10^4$	$\leq 3 \times 10^{-2}$	2.93×10^{-8}	$\leq 1 \times 10^6$	$\leq 4 \times 10^{-3}$	1.52×10^{-7}	$\leq 2 \times 10^4$
¹⁰⁶ Ru	$\leq 1 \times 10^{-1}$	4.21×10^{-7}	$\leq 2 \times 10^5$	2.47×10^{-1}	4.19×10^{-8}	5.9×10^4	4.86	8.33×10^{-7}	5.8×10^6	7.43×10^{-1}	2.99×10^{-5}	2.5×10^4
¹²⁵ Sb	$\leq 3 \times 10^{-2}$	1.70×10^{-7}	$\leq 2 \times 10^5$	$\leq 1 \times 10^{-2}$	1.68×10^{-7}	$\leq 6 \times 10^4$	$\leq 1 \times 10^{-1}$	6.89×10^{-8}	$\leq 1.5 \times 10^6$	$\leq 2 \times 10^{-2}$	1.80×10^{-6}	$\leq 1 \times 10^4$
¹³⁴ Cs	1.98×10^{-2}	1.11×10^{-7}	1.8×10^5	1.30×10^{-1}	9.66×10^{-6}	1.3×10^4	2.55	2.21×10^{-6}	1.2×10^6	1.32×10^{-1}	8.56×10^{-6}	1.5×10^4
¹³⁷ Cs	3.44	8.11×10^{-6}	4.2×10^5	2.51	5.30×10^{-5}	4.7×10^4	7.21	3.36×10^{-6}	2.1×10^6	1.99	1.05×10^{-4}	1.9×10^4
Gross γ (counts min ⁻¹ ml ⁻¹)	1.26×10^6	7	1.8×10^5	1.10×10^6	23	4.8×10^4	5.67×10^6	5	1.1×10^6	1.02×10^6	78	1.3×10^4

^aNo iodine detected in feed.

^bThe condensate is treated further by ion exchange and a modified water-softening process using lime, soda ash, and clay.

^cAverage system decontamination factor, $(\overline{DF})_S$, defined as the feed concentration divided by the average condensate concentration.

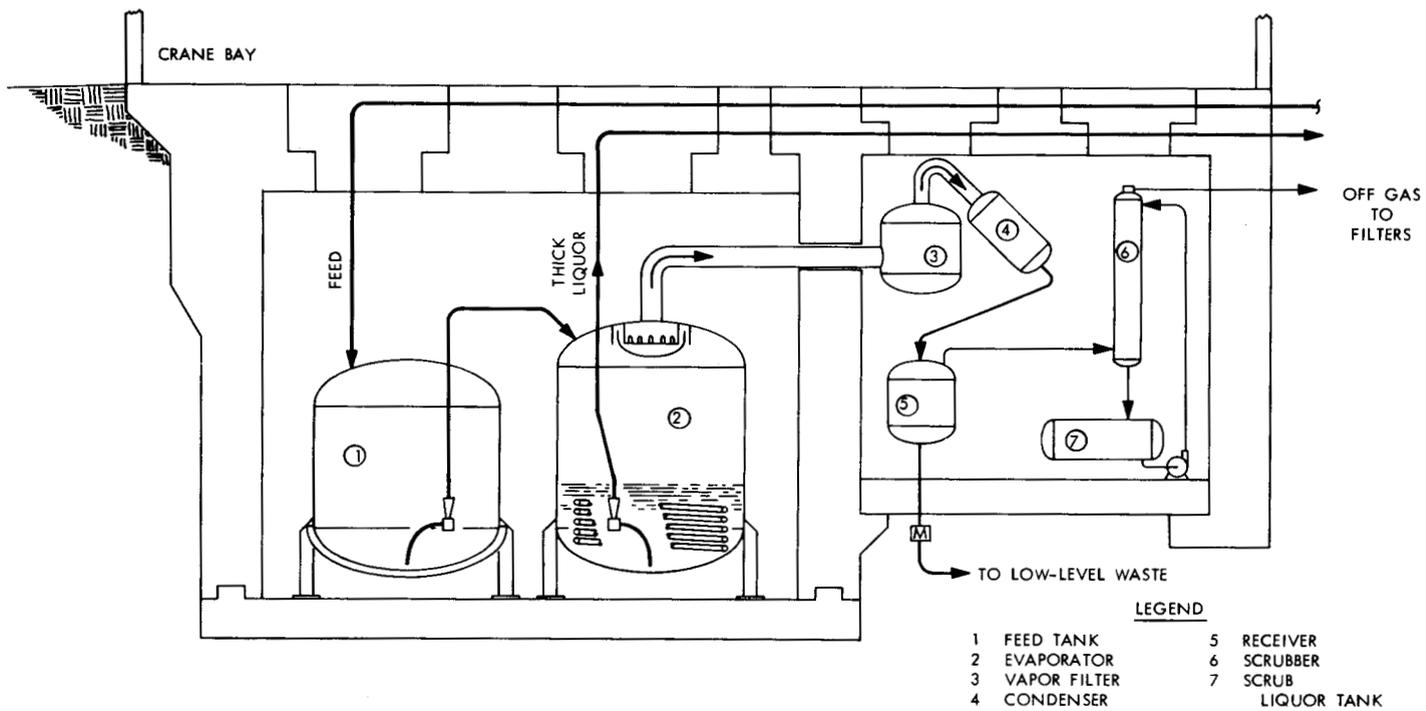


Fig. H-1. ORNL Waste Evaporator and Auxiliary Equipment.

APPENDIX I. DESIGN SPECIFICATIONS FOR EVAPORATORS
AT NUCLEAR POWER PLANTS

Table I-1. Design Specifications for Evaporators at Nuclear Power Plants

Installation [Capacity] (Reactor Type)	Waste Stream Treated	Evaporator Type			Manufacturer	Number of Units	Design Rating			Entrainment Separators	Notes
		Tubes		Circulation			Capacity (gal/min)	Pressure (psia)	DF Equipment = E System = S		
		Internal = I External = E	Horizontal = H Vertical = V								
Arkansas Nuclear One 1 [2568 MW(t)]	Dirty					1	20				Unit 1 uses filters and demineralizers until unit 2 evaporators become available for sharing.
2 [2900 MW(t)] (PWR)	Clean					1	20				
Arnold [1670 MW(t)] (BWR)	Chemical					1					
Big Rock Point [240 MW(t)] (BWR)		(No Evaporator)									
Brown's Ferry 1, 2, and 3 [3293 MW(t)] ea. (BWR)	Low purity					1	30				
Calvert Cliffs 1 and 2 [2450 MW(t)] ea. (PWR)	Dirty	I	H	F	AMF ^a	1	20	5	S: $1_2 = 10^2$ Others = 5×10^2	Perforated plate, sieve tray and wire mesh.	
	Clean	I	H	F	AMF	1	20	5	S: $1_2 = 5 \times 10$ Others = 2.5×10^2	Perforated plate, sieve tray and wire mesh.	
Connecticut Yankee [1825 MW(t)] (PWR)	Dirty					1	15				
	Clean	E		F		2	20		S: 8×10^4 to 2×10^5 gross		See Sect. 7.2 for description of evaporator.
Cook 1 and 2 [3250 MW(t)] ea. (PWR)	Dirty	I			WHTD ^b	1	2		E: 10^6 gross	Wire mesh column.	
	Clean	I				2	30		10^6 gross	Absorption column.	
Cooper [2381 MW(t)] (BWR)	Chemical					1	10				Deep bed demineralizer to be added (in addition to powdex).
Dresden 1 [700 MW(t)] (BWR)		(No Evaporator)									
Dresden 2 and 3 [2527 MW(t)] ea. (BWR)	Chemical	E	V	N	Aqua-Chem. ^c	2	25	45	S: 10^3 gross	Baffle and wire mesh.	One evaporator now in use with one in reserve. Uses Dow B Anti-Foam.
Farley 1 and 2 [2766 MW(t)] ea. (PWR)	Dirty					1	15				
	Clean					1	15				
Fitz Patrick [2436 MW(t)] (BWR)	Chemical	I	V	N		2	20	65			The 0.8-GPM Unit is a turbulent-film evaporator for further concentration of thick liquor.
						1	0.8	Vac. to 165			
Ft. Calhoun [1420 MW(t)] (PWR)	Dirty	I		N		1		16 to 17	E: 10^4 gross		
Ft. St. Vrain [482 MW(t)] (HTGR)		(No Evaporator)									
GINNA [1300 MW(t)] (PWR)	Dirty	I	H	F	AMF	1	2	4	E: 10^6 gross	Splash plate and wire mesh.	Uses Dow H-10 Anti-Foam.
	Clean	I	H	F	AMF	1	12.5		E: 10^6 gross	Perforated plate, sieve tray and wire mesh.	

Table I-1 (continued)

Installation [Capacity] (Reactor Type)	Waste Stream Treated	Evaporator Type			Manufacturer	Number of Units	Design Rating			Entrainment Separators	Notes
		Tubes		Circulation Natural = N Forced = F			Capacity (gal/min)	Pressure (psia)	DF Equipment = E System = S		
		Internal = I External = E	Horizontal = H Vertical = V								
Humboldt Bay [240 MW(t)] (BWR)	Chemical and Low purity	I	V	N	THERMOVAC ^d	1	1	15		None.	Same unit is used for both waste streams.
Indian Point 1 [615 MW(t)] (PWR)	Dirty			F		1	12	25		Equipped but not described.	
Indian Point 2 [2758 MW(t)] (PWR)	Dirty	I	H	F	AMF	1	2			External wire mesh demister.	
Kewaunee [1650 MW(t)] (PWR)	Clean		H	F	AMF	2	12		E: 10 ⁶ gross	External wire mesh demister.	
	Dirty				WHTD	1	2	18	E: 10 ⁴ gross	Absorption tower.	
LaCrosse [165 MW(t)] (BWR)	Clean	I	V			1		Vac.	E: 10 ⁴ gross	Wire mesh.	
	Chemical	I	V	N		1	1	30		Internal and external wire mesh.	
Limerick 1 and 2 [3293 MW(t)] ea. (BWR)	Chemical	E	H	F	UNITECH ^e	2	18.5		E: 10 ⁴ to 10 ⁵ gross	Trays and wire mesh.	
Maine Yankee [2440 MW(t)] (PWR)	Dirty					1	6 to 8	Vac. to 65	S: 10 ⁴ gross		
	Clean	E	V	F		1	25		S: 10 ⁴ gross		
Millstone Pt. 1 [2011 MW(t)] (BWR)	Chemical	E	V	N		2			S: I ₂ = 50 Others = 10 ³	Wire mesh demister.	
Monticello [1670 MW(t)] (BWR)		(No Evaporators)									
Nine Mile Point [1850 MW(t)] (BWR)	Chemical	I	V	N	SWENSON ^f	1	10	15		Wire mesh.	Being replaced by 25-GPM forced-circ. unit made by Horton Process Industries.
North Anna 1 and 2 [2652 MW(t)] ea. (PWR)	Dirty					1	6				
	Clean					1	20				
North Anna 3 and 4 [2763 MW(t)] (PWR)	Dirty					1	6				
	Clean					1	20				
Oconee 1 [2452 MW(t)] 2 and 3 [2584 MW(t)] ea. (PWR)	Dirty	I	H	F	Aqua-Chem.	1	7.5		S: 10 ⁵ gross	Wire mesh with spray nozzles.	
	Clean	I	H	F	Aqua-Chem.	1	7.5		S: 10 ⁵ gross	Wire mesh with spray nozzles.	
Oyster Creek [1930 MW(t)] (BWR)	Chemical and Low purity	I		N		1				Wire mesh column.	Troubles with tubes plugging.
Palisades [2212 MW(t)] (PWR)	Dirty				AMF	1	30				
	Clean				AMF	1	30				
Peach Bottom 1 [115 MW(t)] (HTGR)		(No Evaporator)									

Table I-1 (continued)

Installation [Capacity] (Reactor Type)	Waste Stream Treated	Evaporator Type			Manufacturer	Number of Units	Design Rating			Entrainment Separators	Notes
		Tubes		Circulation			Capacity (gal/min)	Pressure (psia)	DF Equipment = E System = S		
		Internal = I External = E	Horizontal = H Vertical = V								
Peach Bottom 2 and 3 [3294 MW(t)] ea. (BWR)		(No Evaporators)									Addition of a 20-GPM Evaporator was considered earlier.
Pilgrim 1 [1998 MW(t)] (BWR)	Chemical	I	H	F		1			Wire mesh with spray nozzles.		Spray-Film Vapor Compression Evaporator.
Point Beach 1 and 2 [1518 MW(t)] ea. (PWR)	Dirty	I	H	F	AMF	1	2	2	E: 10 ⁶ gross	Perforated plate, sieve trays and wire mesh.	Waste circulates between feed tank and dirty waste evaporator; anti-foaming agent is Dow H-10. No anti-foam used in clean waste.
	Clean	I	H	F	AMF	1	12.5	6-7	E: 10 ⁶ gross	Perforated plate, sieve trays and wire mesh.	
Point Beach 1 and 2 [1518 MW(t)] ea. (PWR)	Dirty	E	V	F	S & W ^g	1	35	30	S: 10 ⁴ gross	Distillation trays.	This evaporator is replacing the dirty waste unit above.
Prairie Island 1 and 2 [1650 MW(t)] ea. (PWR)	Dirty	I				1	2		E: 10 ⁴ gross	Flexiring packing and wire mesh absorption tower.	
	Dirty Clean	I	H	F	WHTD	1 1 ea.	5 15		E: 10 ⁴ to 10 ⁵ gross E: 10 ⁶ gross	Wire mesh.	
Quad-Cities 1 and 2 [2511 MW(t)] ea. (BWR)		(No Evaporators)									
Robinson - 2 [2200 MW(t)] (PWR)	Dirty	I	H	F	AMF	1	2	4	E: 10 ⁶ gross	Perforated plate, sieve tray and wire mesh.	Uses Dow H-10 Anti-Foam
	Clean	I	H	F	AMF	2		6-7	E: 10 ⁶ gross	Perforated plate, sieve tray and wire mesh.	
San Onofre 1 [1347 MW(t)] (PWR)		(No Evaporators)									
San Onofre 2 and 3 [3410 MW(T)] ea. (PWR)	Dirty		H			1	50				
Sequoyah 1 and 2 [3423 MW(t)] ea. (PWR)	Dirty				WHTD	1	5	18	E: 10 ⁵ gross	Packing rings and wire mesh.	
	Clean				WHTD	2	30	18	E: 10 ⁵ gross	Trays in absorption tower.	
Shippingport [505 MW(t)] (PWR)	Dirty	I	V		Mech. Equip. ^h	1	1.67		E: 10 ⁶ gross		Vapor compression (as installed).
Surry 1 and 2 [2441 MW(t)] ea. (PWR)	Dirty	E	H	F		1	6				
	Clean	E	V	F		2	2	30	E: 10 ⁴ to 10 ⁵ gross		
Three Mile Island 1 [2535 MW(t)] 2 [2772 MW(t)] (PWR)	Dirty					1	12		E: 10 ⁴ gross		Unit 1 has powdex system. Unit 2 has deep-bed regenerated ion exchangers.
	Clean					2					
Turkey Point 3 and 4 [2097 MW(t)] ea. (PWR)	Dirty	I	H	F	AMF	1	3		E: 10 ⁶ gross	Perforated plate, sieve tray and wire mesh	Modified AMF Unit.
Vermont Yankee [1593 MW(t)] (BWR)		(No Evaporators)									

Table I-1 (continued)

Installation [Capacity] (Reactor Type)	Waste Stream Treated	Evaporator Type			Manufacturer	Number of Units	Design Rating			Entrainment Separators	Notes
		Tubes		Circulation Natural = N Forced = F			Capacity (gal/min)	Pressure (psia)	DF Equipment = E System = S		
		Internal = I External = E	Horizontal = H Vertical = V								
Yankee-Rowe [600 MW(t)] (PWR)	Dirty	E	V	F		1	6			Cyclone.	
Zion 1 and 2 [3391 MW(t)] ea. (PWR)	Dirty	I	H	F	Aqua-Chem.	1	15	15	E: 10 ⁶ gross	Wire mesh with spray nozzles.	Feed sprays down onto heater tubes.
	Clean			F	WHTD	1	20	18	E: 10 ⁶ gross	Absorption tower.	

^aAmerican Machine and Foundry Company, York, Pennsylvania.

^bWestinghouse Heat Transfer Division, Monroeville, Pennsylvania.

^cAqua-Chem., Inc., Milwaukee, Wisconsin.

^dThermovac Industries Corp., Copiague, New York.

^eThe Unitech Company, Union, New Jersey.

^fSwenson Evaporator Company, Harvey, Illinois.

^gStone and Webster Engineering Corp., Boston, Massachusetts.

^hMechanical Equipment Co., New Orleans, Louisiana.

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