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A Model of Iodine Transport and Reaction Kinetics in a Nuclear Fuel Reprocessing Plant

Wallace Davis, Jr.

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety & Safeguards
Under Interagency Agreement ERDA 40-549-75

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IN A NUCLEAR FUEL REPROCESSING PLANT**

Wallace Davis, Jr.

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A MODEL OF IODINE TRANSPORT AND REACTION KINETICS
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ABSTRACT

A model is presented to describe the time-dependent flow and retention of stable iodine isotopes and, additionally, the extent of radioactive decay of ^{131}I in a nuclear fuel reprocessing plant. The plant, which is similar to, but slightly more complex than, Allied-General Nuclear Services' plant at Barnwell, South Carolina, consists of 16 units of equipment such as a voloxidizer or graphite burner, fuel dissolver, solvent extractors, storage tanks, vaporizers, primary iodine sorbers, and silver zeolite. The rate of accumulation of bulk and radioactive iodine in these units and in the environment is described in terms of two sets of 19 differential equations that contain parameters representing experimental data, including flow rates that are functions of physical or chemical kinetics in each process unit. In the absence of experimental data, the reaction rates were assumed to obey first-order kinetics with individual time constants related to estimates of unit capacity for iodine. Isotopic exchange equilibrium is assumed to be maintained in all units.

Based on the meager experimental data and "reasonable" values of bulk-iodine retention times for use in the kinetic processes, reasonable time-dependence of iodine retention factors (RFs) [alternatively designated as decontamination factors (DFs) or confinement factors (CFs)] by the plant has been calculated. In particular, RFs for a new plant in excess of 10^6 for stable iodine and ^{127}I decrease to the range of 10^3 to 10^2 as plant operating times exceed 50 to 100 days. The RFs for ^{131}I also decrease initially, for a period of ~ 10 days, but then increase by several orders of magnitude due to radioactive decay and isotopic exchange. Generally, the RFs for ^{131}I exceed those for stable iodine by factors of 10^4 or larger, depending on the operating time and on many other variables.

The computer programs written to solve the two sets of 26 mass flow rates and to integrate the two sets of 19 differential equations can easily be modified to utilize experimental data which will be obtained in the future, including data that might demonstrate one or more of the rate processes not to be first-order.

1. INTRODUCTION

Radioactive iodine isotopes, both short-lived ^{131}I (half-life of 8.05 days) and the long-lived ^{129}I (half-life of 16 million years), are generated in nuclear fuels; very small amounts will be discharged to the environment both at the reactors, where they are formed, and at fuel reprocessing plants, where they will be encapsulated for permanent storage. The Environmental Protection Agency has issued^{1,2} standards that will require normal operations within the uranium fuel cycle to be conducted in such a manner as to provide reasonable assurance that: (a) the annual dose equivalent does not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public; (b) the quantity of ^{129}I released to the environment per gigawatt-year of power produced by the entire fuel cycle does not exceed 5 millicuries.

A Light-Water Reactor (LWR) fuel reprocessing plant, such as that of Allied-General Nuclear Services at Barnwell, South Carolina,³ annually will process fuel that contained 1500 metric tons of heavy metal (MTHM = uranium + plutonium) as charged to reactors which produce ~42,000 MW(e)-year of energy during 1 year of operation. This 1500 MTHM will contain more than 50 Ci ^{129}I (>300 kg) and, when processing is performed 160 days after discharge of fuel from the reactors, more than 1000 Ci ^{131}I (>10 mg). This spent fuel will pass through⁴ process operations involving fuel dissolution, solvent extraction, sorption in solutions [such as $\text{Hg}(\text{NO}_3)_2\text{-HNO}_3$], and sorption on silver-exchanged zeolites and on ion exchange resins. These and other unit operations, such as neutralization of solutions and distillation, are parts of an extremely complicated system of iodine transport to "a few" final storage stations.

A quantitative description of the movement of iodine in a fuel reprocessing plant on the basis of laboratory experimental data does not appear to be possible at the present time since many of the plant processes have not been studied in sufficient detail. For example, the kinetics of iodine sorption in $\text{Hg}(\text{NO}_3)_2\text{-HNO}_3$ solution or on silver-exchanged zeolites can not be determined on the basis of existing data. In the absence of

laboratory data, descriptions of the chemistry and kinetics of a number of the processes involving iodine retention may not be possible unless appropriate data are obtained at the fuel reprocessing plant itself.

A nuclear fuel reprocessing plant, such as that at Barnwell, is designed to operate, and probably will operate, without the maintenance of constant flows of materials from one equipment unit to another. Because of expected discontinuities in such flows, mathematical calculations concerning the movement of iodine through an actual plant could become extremely complicated. The time scales of flow discontinuities are not known but may be in the range of a few days to a few weeks. However, much can be learned about the kinetics of many chemical or physical processes from a model that assumes some type of constancy or regularity of these flows.

The present report is concerned with a model of the time-dependent flow of iodine, stable and radioactive, through a fuel reprocessing plant. This plant was first described by Finney et al.⁴ in a generic cost/benefit analysis of the environmental impacts of reprocessing LWR fuel; it is similar to, but somewhat more complicated than, the Barnwell plant. The mathematical model of the conceptual plant is based on particular, potentially realistic assumptions of continuous flow of iodine from one unit to the next; on the radioactive decay of a short-lived isotope; on physical and chemical retention of iodine in various process units; and on the discharge of part of the iodine into the environment. Transfer of iodine and decay of ^{131}I in the conceptual plant under steady state conditions were described by Davis et al.⁵ in a generic cost/benefit analysis of the environmental impact of reprocessing High-Temperature Gas-Cooled Reactor (HTGR) fuel.

Two of the primary purposes of this report are to identify most of the variables that control the flow of iodine and to identify some of the various types of laboratory data, such as kinetic rate constants and equipment holdup times, that could simplify the description of iodine flow in the reprocessing plant. By identifying these data, the extent to which such a plant must serve as an experimental unit could be reduced.

It should be noted that iodine is shown to be discharged to the environment in two streams, Q150E and Q160E. These, and the corresponding environmental sinks, units 17 and 18, are retained as separate items in the mathematical analysis to differentiate between iodine that is discharged in the conventional off-gas stream (Q160E) and iodine discharged with steam (Q150E). The model plant is assumed to discharge excess water as steam carrying volatile components such as iodine, but not as liquid water, which would contain many radioactive nuclides at low concentrations.

Flows of total iodine or ^{131}I are expressed in Fig. 1 by the letter Q followed by four alphanumeric characters. The first two characters specify the unit from which iodine flows; the second two characters specify the unit to which iodine flows. Each flow variable has two possible subscripts; subscript 1 refers to total iodine, and subscript 2 refers to the short-half-lived isotope ^{131}I . For example,

Q0001(1) = the rate of flow of total iodine from fuel storage to the graphite burner or voloxidizer;

Q0103(2) = the rate of flow of ^{131}I from unit 1 to unit 3;

Q1011(1) = the rate of flow of total iodine from unit 10 to unit 11;

Q160E(1) = the rate of flow of total iodine from unit 16 to the environment.

Equations that describe the flow of total iodine or ^{131}I in the fuel reprocessing plant are expressed as a function of flows into and out of individual units as follows:

$$(\text{Accumulation of iodine in unit K}) = (\text{Flow of iodine into unit k}) - (\text{Flow of iodine out of unit K}) - (\text{Decay of iodine in unit K}) \quad (\text{A})$$

For example,

$$\dot{N}_1 = Q0001(1) - [Q0102(1) + Q0103(1)] - \lambda n_1 \quad (\text{B-1})$$

and

$$\dot{n}_1 = Q0001(2) - [Q0102(2) + Q0103(2)] - \lambda n_1, \quad (\text{B-2})$$

where \dot{N}_1 and \dot{n}_1 represent the rates of accumulation of total iodine and of ^{131}I , respectively, in unit 1. The flow terms Q0001(1), Q0001(2), etc., are described above, while the term λn_1 corresponds to the decay of ^{131}I

in unit 1. Due to its long half-life, ^{129}I is stable in the context of this report since the longest real time of significance is the lifetime (30 to 40 years) of the fuel reprocessing plant.

Terminology of equations such as (B-1) and (B-2), and their counterparts for each unit of equipment of Fig. 1, has been modified in this report to be suggestive of FORTRAN programming. This permits a close identification with the computer programs that are used to solve the mathematical model for the desired quantities. Calculation of these quantities is based on numerical integration of two sets of 19 differential equations, each set involving 27 flows, one radioactive-decay constant, and 15 physical or chemical rate processes. The total-iodine inventory and its rate of accumulation in unit K (Fig. 1) are symbolized by $\text{EN}(K,1)$ and $\text{DER}(K,1)$, respectively, instead of the N_k and \dot{N}_k , which would correspond (with $k = 1$) to Eq. (B-1). The ^{131}I inventory and its rate of accumulation in unit K are symbolized by $\text{EN}(K,2)$ and $\text{DER}(K,2)$, respectively, instead of n_k and \dot{n}_k , which would correspond to Eq. (B-2). Analytical descriptions of time derivatives (DER) of inventories of iodine in the various units, with $L = 1,2$, are given by Eqs. (1) to (19).

$$\text{DER}(1,L) = [\text{Q0001}(L) - \text{T}(1)] - [\text{Q0102}(L) + \text{Q0103}(L)] , \quad (1)$$

$$\begin{aligned} \text{DER}(2,L) = & [\text{Q0102}(L) + \text{Q0402}(L) + \text{Q0502}(L) + \text{Q1202}(L) \\ & + \text{Q1402}(L) - \text{T}(2)] - [\text{Q0209}(L) + \text{Q0216}(L)] , \end{aligned} \quad (2)$$

$$\text{DER}(3,L) = [\text{Q0103}(L) + \text{Q1303}(L) - \text{T}(3)] - [\text{Q0304}(L) + \text{Q0305}(L)] , \quad (3)$$

$$\text{DER}(4,L) = [\text{Q0304}(L) - \text{T}(4)] - [\text{Q0402}(L) + \text{Q0409}(L)] , \quad (4)$$

$$\text{DER}(5,L) = [\text{Q0305}(L) - \text{T}(5)] - [\text{Q0502}(L) + \text{Q0506}(L) + \text{Q0507}(L)] , \quad (5)$$

$$\text{DER}(6,L) = \text{Q0506}(L) - \text{T}(6) , \quad (6)$$

$$\text{DER}(7,L) = [\text{Q0507}(L) - \text{T}(7)] - [\text{Q0713}(L) + \text{Q0714}(L)] , \quad (7)$$

$$\text{DER}(8,L) = [\text{Q1008}(L) + \text{Q1308}(L) - \text{T}(8)] - [\text{Q0810}(L) + \text{Q0815}(L)] , \quad (8)$$

$$\text{DER}(9,L) = [\text{Q0209}(L) + \text{Q0409}(L) - \text{T}(9)] - [\text{Q0910}(L) + \text{Q0919}(L)] , \quad (9)$$

$$\text{DER}(10,L) = [\text{Q0810}(L) + \text{Q0910}(L) - \text{T}(10)] - [\text{Q1008}(L) + \text{Q1011}(L)] , \quad (10)$$

$$\text{DER}(11,L) = [\text{Q1011}(L) - \text{T}(11)] - \text{Q1112}(L) , \quad (11)$$

$$\text{DER}(12,L) = [Q1112(L)-T(12)]-Q1202(L) , \quad (12)$$

$$\text{DER}(13,L) = [Q0713(L)-T(13)]-[Q1303(L)+Q1308(L)] , \quad (13)$$

$$\text{DER}(14,L) = [Q0714(L)-T(14)]-Q1402(L) , \quad (14)$$

$$\text{DER}(15,L) = [Q0815(L)-T(15)]-Q150E(L) , \quad (15)$$

$$\text{DER}(16,L) = [Q0216(L)-T(16)]-Q160E(L) , \quad (16)$$

$$\text{DER}(17,L) = Q150E(L)-T(17) , \quad (17)$$

$$\text{DER}(18,L) = Q160E(L)-T(18) , \text{ and} \quad (18)$$

$$\text{DER}(19,L) = Q0919(L)-T(19) \quad (19)$$

In these equations, $T(K)$ corresponds to λn_k of Eq. (B-2) and is defined as:

$$T(K) \equiv EL*EN(K,2) , \quad (20)$$

where

EL = the radioactive decay constant, λ , of ^{131}I (0.0861/day), and

$EN(K,2)$ = the inventory of ^{131}I in unit K .

The two sets of 19 differential equations, Eqs. (1) to (19), of the time-dependent model of iodine accumulation can be integrated when we specify the initial inventory in each unit, the initial value of each flow, and a method for evaluating the time dependence of these flows. In this report, we have considered only a new plant in which all initial inventories are zero and all initial flow rates are zero except those into unit 1, Q0001(1) and Q0001(2). The value of Q0001(1) is set equal to 1.0 (i.e., 1 day's input/day), and the value of Q0001(2) is set equal to 1.0D-7* in accord with previous discussions⁷ concerning the activity of ^{131}I in an LWR fuel reprocessing plant, wherein the fuel is processed 160 days after discharge from the reactor. The assumptions used to calculate the remaining two sets of 26 flows and the use of available experimental data are described in the next section.

*The D refers to double precision. Thus, 1.0D-7 means $1. \times 10^{-7}$ in double-precision calculations.

3. EXPERIMENTAL DATA AND ASSUMPTIONS CONCERNING FLOWS

Most of the available experimental information pertaining to iodine flow in process units shown in Fig. 1 are summarized in Table 1 as DFs, as fractions (A13 or A51 and A52) of iodine flowing in one of two or three possible directions, as the ratio of flows (A1, A3) in two possible directions, or as the fractional rate of recycle (due to sparging, purging, or venting) of iodine from storage tanks (RECYCL and HLVENT). The values of these variables are not known very accurately; in addition, all values depend upon how a particular unit of process equipment is operated. For example, the variable RECYCL will be as large as 0.00216 only if the sparge or purge rate at the MLW storage tank, Fig. 1, is sufficiently low so that iodine in liquid and vapor phases is in thermodynamic equilibrium and the equilibrium conditions correspond⁵ to an iodine equilibrium concentration ratio $[C(\text{liq})/C(\text{vap})]$ of 5000.

Each pair of equations, (1) to (19), contains terms for iodine entering a unit and iodine leaving a unit; in the case of units 17 and 18, each the environment, and unit 19, containing permanently isolated iodine, only ^{131}I leaves the unit, by decay. The model of this report is based on the assumption that the rate at which iodine (total, stable, or radioactive) leaves a unit is proportional to the amount of iodine in the unit (more specifically, the degree to which the unit is saturated with iodine). This approach was used previously⁷ and is expressed as:

$$\begin{aligned} \text{Total Flow of } I_2 \text{ out of unit } K &= [\text{Total Flow of } I_2 \text{ into unit } K - T(K)] \\ &\quad *EN(K,1)/ENMAX(K). \end{aligned} \quad (21)$$

Here,

$ENMAX(K)$ = the capacity of unit K for iodine.

To maintain consistency with the definition of $EN(K,1)$, $ENMAX(K)$ is expressed in units of days of iodine input to the plant. For example, the graphite burner or voloxidizer unit 1 may have a capacity of a few hours of input of iodine; that is, after a few hours of operation, iodine leaves unit 1 as fast as it enters the unit, except for radioactive decay.

Table 1. Experimental information used in analyzing the reference fuel reprocessing plant

Variable	Definition and value	Reference
Q0001(1)	Set, for convenience, equal to 1.000 units of iodine input per day.	
Q0001(2)	Set equal to $1.0D-7$ times Q0001(1); that is, the mass flow of ^{131}I will be in the order of $1.0D-7$ times the total-iodine flow.	7
A1	This is the ratio, $Q0102(L)/Q0103(L)$, of iodine that vaporizes in the head-end step (unit 1 of Fig. 1) to that which remains in the fuel particles. Vaporized iodine enters the off-gas system (unit 2) while iodine remaining in the fuel flows to the dissolver (unit 3) and becomes part of the more complex liquid stream (unit 5, etc.). = 0.0 for an LWR fuel reprocessing plant not having a voloxidizer system. = 0.6 approximately, for a voloxidizer unit applicable to LWR and LMFBR fuel reprocessing plants. = 0.67 approximately, for the graphite burner system of an HTR fuel reprocessing plant.	8 9
DF2	This is the DF of unit 2 [which might be $Hg(NO_3)_2-HNO_3$ solution or other primary iodine-removal unit] for a nonradioactive iodine species. It also is equal to $[Q0209(L)+Q0216(L)]/Q0216(L)$. = 100. very conservatively, for $Hg(NO_3)_2-HNO_3$ solutions. = 1000. conservatively, for the Iodox process.	10 11
A3	This is the ratio $[Q0304(L)/Q0305(L)]$, similar to A1, of iodine that vaporizes in the dissolver (unit 3 of Fig. 1) to that which remains in the liquid. Vaporized iodine flows to unit 4 while unvaporized iodine flows to the solvent extraction system (unit 5) and remains in the liquid system.	

Table 1. (Continued)

Variable	Definition and value	Reference
	= 9.0 (i.e., 90% vaporized to unit 4) for simple dissolving.	12
	= 99. or 99.5 when iodine-evolution techniques are used.	12,13
DF4	This is the DF of unit 4, which may be the same as or different from DF2. It is also equal to $[Q0402(L)+Q0409(L)]/Q0402(L)$.	
A51	This is the fraction, $Q0502(L)/[Q0502(L)+Q0506(L)+Q0507(L)]$, of iodine that is vaporized from the solvent extraction system (unit 5), thereby reporting to the off-gas system. This parameter is not well known. = 0.04 in the calculations of this report.	
A52	This is the fraction, $Q0506(L)/[Q0502(L)+Q0506(L)+Q0507(L)]$, of iodine that flows to and remains in the solvent purification system (unit 6). This parameter also is not well known. = 0.06 in the calculations of this report.	
DF7	This is the DF, $[Q0713(L)+Q0714(L)]/Q0713(L)$, of unit 7, possibly a high-level waste (HLW) evaporator system. This parameter is not well defined. = 3. in the calculations of this report.	
DF8	This is the DF, $[Q0810(L)+Q0815(L)]/Q0815(L)$, of unit 8, possibly an iodine-removal partial evaporator. Efficiencies of evaporators depend on many variables, but DF8 may not be large. = 4.0 in the calculations of this report.	
A91	This is the fraction, $Q0910(L)/[Q0910(L)+Q0919(L)]$, of iodine that flows from unit 9 to unit 10, thereby being recycled to the plant rather than to the "permanent" fixation unit 19.	

Table 1. (Continued)

Variable	Definition and value	Reference
	<ul style="list-style-type: none"> = 1. if no fixation is performed. = 0. if all iodine from unit 9 goes to unit 19; but A91 must be greater than 0. for purposes of computation. 	
DF10	<p>This is the DF, $[Q1008(L)+Q1011(L)]/Q1008(L)$, of unit 10, the MLW evaporator. This parameter may be very large, depending on the design and care of operation of the unit.</p> <ul style="list-style-type: none"> = 100. in the calculations of this report. 	14
A13	<p>This is the fraction, $Q1303(L)/[Q1303(L)+Q1308(L)]$, of iodine leaving unit 13, a nitric acid recovery system, that enters unit 3.</p> <ul style="list-style-type: none"> = 0.0 if iodine is not recycled to the dissolver system. = <1.0 if iodine is recycled, in recovered HNO₃, to the dissolver. 	
R(=RECYCL)	<p>Fractional rate of recycle of iodine from the MLW storage tank.</p> <p><u><0.00216</u> .</p>	5
HLVENT	<p>Fractional rate of recycle of iodine from the HLW storage system.</p>	

Equation (21) describes one of the assumptions that defines the model of this report. A second assumption is that iodine removal in each equipment unit (units 6 and 17 through 19 excepted since they are infinite sinks) is described by the first-order kinetic Eq. (22):

$$S(K) = 1 - \exp[-\Lambda(K)*T] , \quad (22)$$

where

$S(K) = EN(K,1)/ENMAX(K)$, the fraction of the capacity of unit K already used;

$\Lambda(K)$ = the time constant for iodine retention in unit K (day^{-1}); and

T = time (days of reprocessing plant operation under the ideal conditions of constant iodine input and the absence of any flow disturbances). [This T should not be confused with $T(K)$ defined in Eq. (20).]

The assumption of first-order kinetics is made because of the absence of experimental data on rates of reaction of iodine in the various units of Fig. 1. It is recognized that this assumption is not accurate for all units, particularly the silver zeolite bed of unit 16 and the ion exchange bed of unit 15. Further discussion of reaction rates is included in Sect. 5. However, regardless of how $S(K)$ is calculated, it is used to evaluate flows according to Eq. (21), as shown in detail in Appendix A.

Equations (21) and (22) are written to apply to total iodine. However, an additional assumption concerning the model is that complete isotopic exchange occurs in each of the 16 units (1-5, 7-16) of equipment of Fig. 1. As a result of this assumption, Eqs. (21) and (22) also apply to ^{131}I . Such an assumption is nearly correct as it pertains to the flow of iodine species from a fuel dissolver, the solvent extraction system, waste storage tanks, distillation units, $\text{Hg}(\text{NO}_3)_2\text{-HNO}_3$ scrubbers (used in units 2 and 4 at Barnwell³), the Iodex system,¹¹ and some other possible components of a fuel reprocessing plant. Assumption of complete exchange of molecular-iodine species also probably applies to the flow of iodine in and through silver zeolite, as previously discussed;⁷ however, there is uncertainty concerning the degree of exchange of iodine present in organic iodides.

The quantities $\Lambda(K)$ are actually calculated from the equation:

$$\Lambda(K) = \ln 2 / \text{TENMAX}(K) , \quad (23)$$

where $\text{TENMAX}(K)$ is a measure of iodine-retention time in unit K . Individual values and definitions of $\text{TENMAX}(K)$ are given in Appendix B.

Two other specifications are used in the present model, namely, that iodine flow from both the MLW and I.W. storage systems, units 11 and 14 of Fig. 1, is controlled by reprocessing-plant operators independently of flows into these units. In both cases, the flow of iodine from the unit is assumed to be proportional to the inventory of iodine in the unit. This corresponds to a purge if there is flow, or to zero if there is no purge.

Based on the definitions and specifications given above, the following sequence of operations leads to determination of all flow rates.

1. Solve the five pairs ($L = 1, 2$) of flow equations, (24) to (28).

$$Q0103(L) = [Q0001(L) - T(1)] * S(1) , \quad (24)$$

$$Q0102(L) = Q0103(L) * A1 , \quad (25)$$

$$Q1112(L) = R * \text{EN}(11, L) , \quad (26)$$

$$Q1202(L) = Q1112(L) * S(12), \text{ and} \quad (27)$$

$$Q1402(L) = \text{HLVENT} * \text{EN}(14, L) . \quad (28)$$

2. Solve the system of 18 simultaneous equations, expressed in matrix form in Eq. (29), by numerical methods.¹⁵ It should be noted that, for brevity, $S(K)$ and $T(K)$ are expressed as SK and TK , and the subscript (L) has been omitted from flow terms in this equation. It should also be noted that $A91$ occurs as $1/A91$. To avoid numerical difficulties, $A91$ should always be set to a value greater than 0.0, even if all the iodine reaching unit 9 is permanently fixed. In this case, a value such as $A91 = 1.0D-10$ is effectively equivalent to $A91 = 0.0$.

3. Solve the final three pairs of equations, (30) to (32).

$$Q0919(L) = Q0910(L) * (1 - A91) / A91 , \quad (30)$$

$$Q150E(L) = [Q0815(L) - T(15)] * S(15), \text{ and} \quad (31)$$

$$Q160E(L) = [Q0216(L) - T(16)] * S(16) . \quad (32)$$

Following evaluation of flows according to Eqs. (24) through (32), the two sets of 19 differential equations, (1) to (19), can be integrated by numerical methods.¹⁶

The entire process of evaluating the two sets of 26 flows and then integrating the two sets of 19 differential equations by the methods outlined above requires less than 0.1 sec per time step with the IBM 360/91 computer. In the present studies, initial time steps were 0.02 days and were increased to 5 and 10 days after 100 days or more of plant operation. Computer execution time can be shortened ~30% on the IBM 360/91 as described in Appendix C. However, programs listed in Appendix C are based on Steps 1, 2, and 3 (above).

4. EXAMPLES OF CALCULATIONS

Examples of calculated relative flow rates, of plant RFs, of unit DFs, of relative radioactivities, and of total iodine inventories are shown in Figs. 2 to 12. The first five figures are for Case 1, which corresponds to Case 2a of Finney et al.⁴ and of Davis et al.⁵ Case 1 of this report differs from Case 1 of refs. 4 and 5 by having an iodine-removal ion exchanger (unit 15); in other aspects, it is the same as Case 1 of these references. For example, only 90% of the contained iodine is vaporized from the dissolver solution, and iodine fixation is not employed. Figures 2 and 3 contain plots of relative flows of iodine in some of the liquid and gasborne streams during the first 500 days of operation of a plant initially containing no iodine. As expected, the flows all increase; some of the flows attain constant values, corresponding to steady state conditions and to saturation of various units with iodine, while others continue to increase. The curves in these figures are determined by the particular values of input parameters. Those values used to derive Figs. 2 to 6 are listed in Table 2 under Case 1. Two parameters, namely TENMAX(11) and TENMAX(14), in this table require further comment

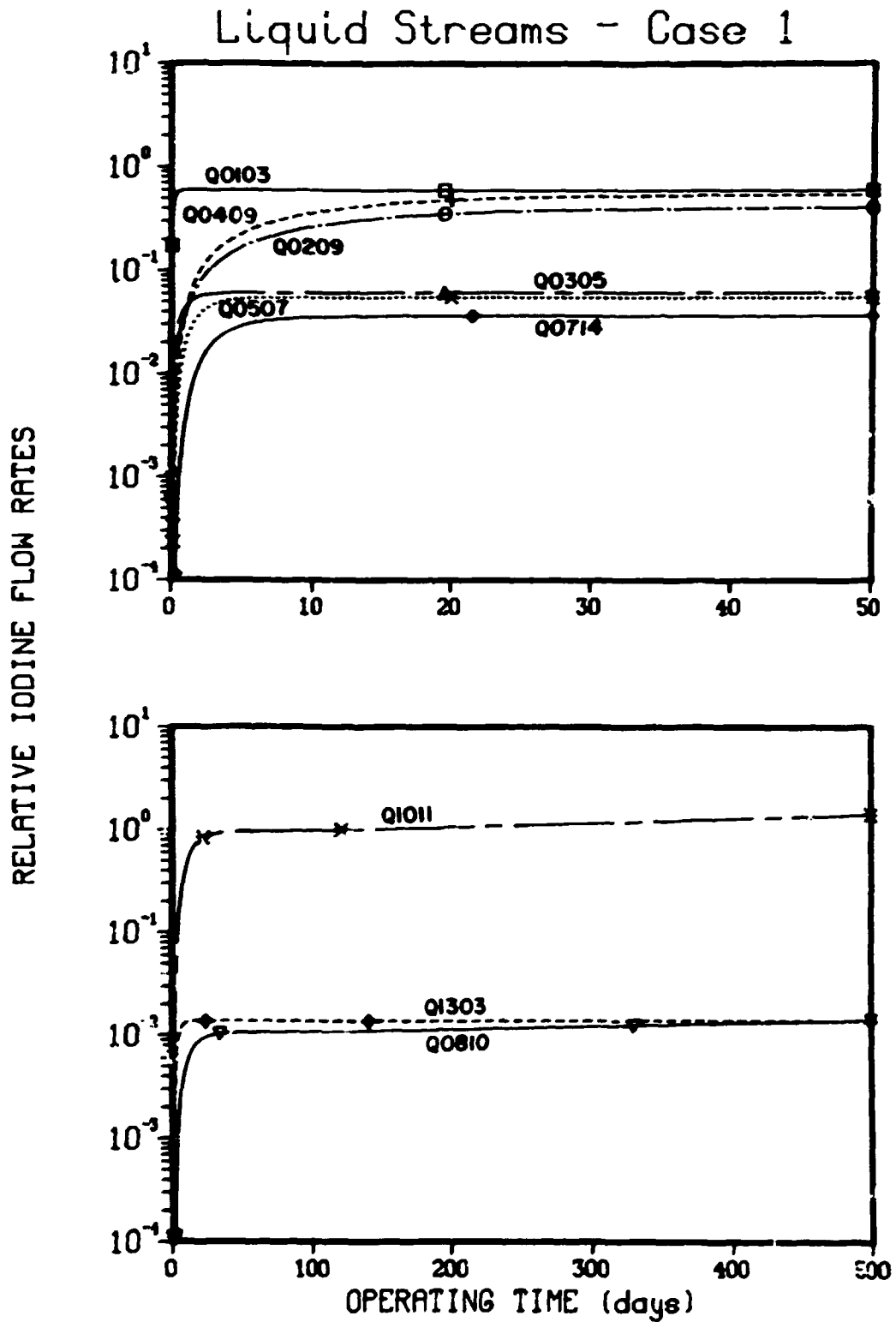


Fig. 2. Relative total-iodine flow rates in liquid streams, Case 1.

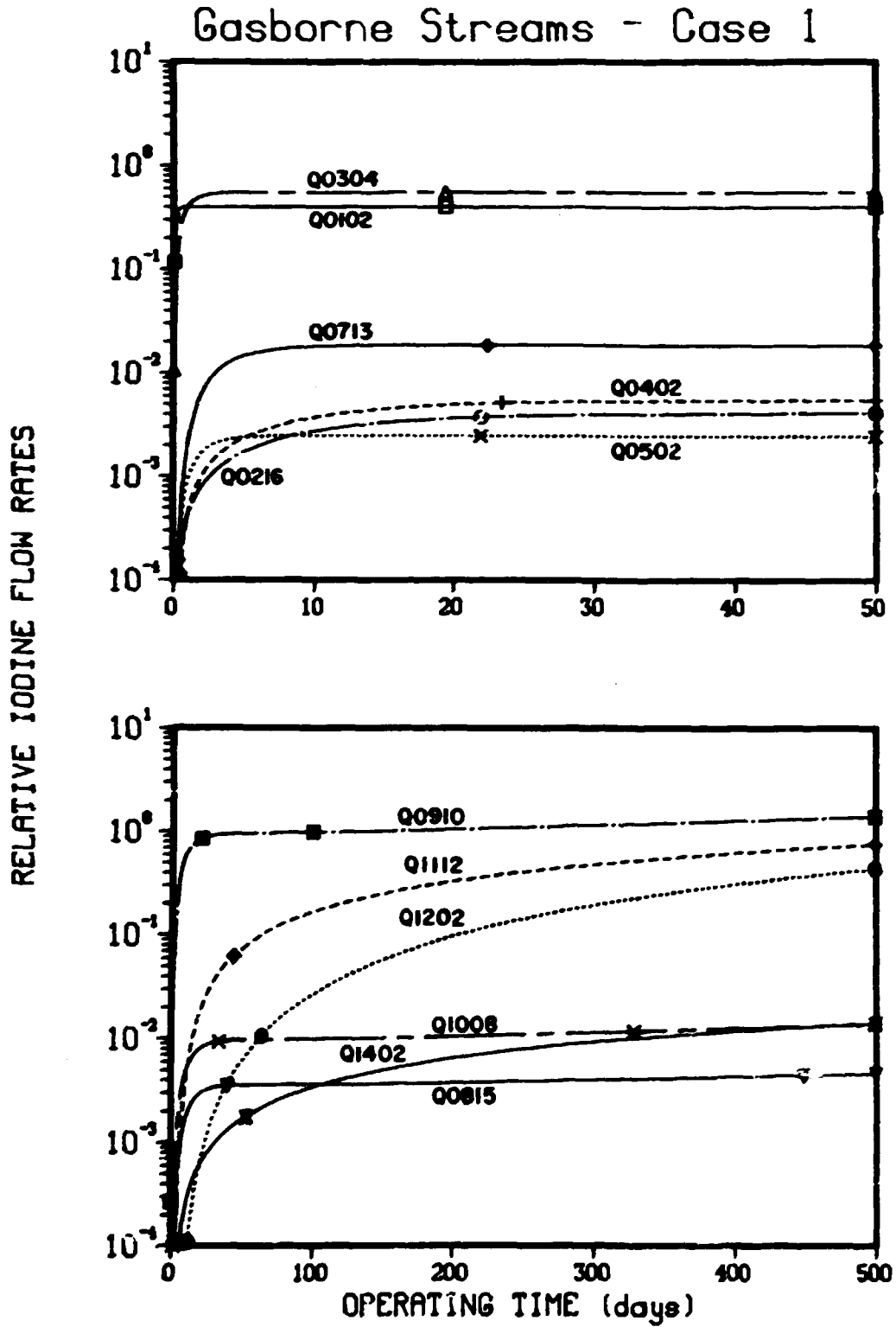


Fig. 3. Relative total-iodine flow rates in gasborne streams, Case 1.

Liquid and Gasborne Streams - Case 1

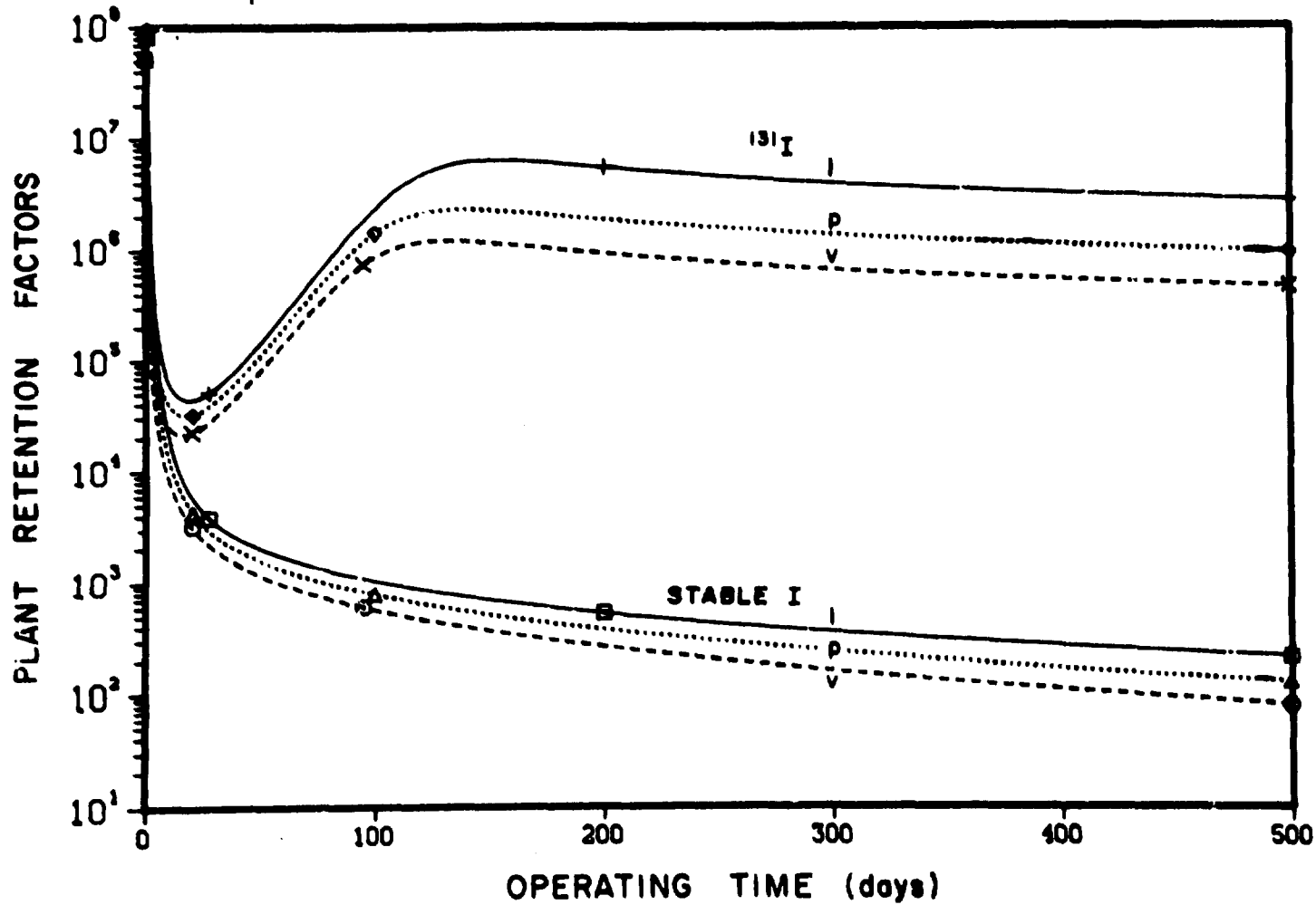


Fig. 4. Plant retention factors for total iodine and ¹³¹I in liquid (l) and vapor (v) streams and for the composite streams (p), Case 1.

Case 1

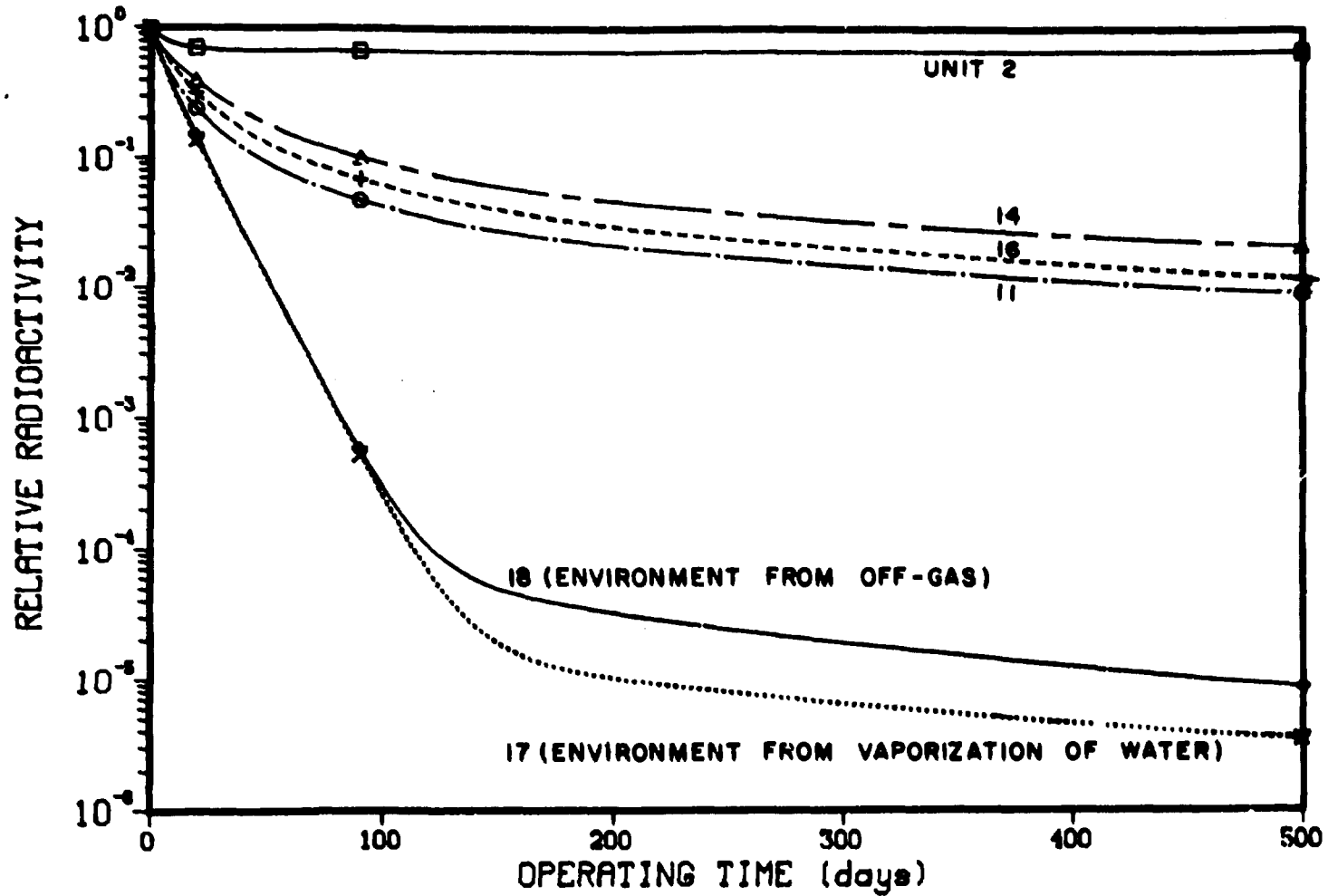


Fig. 5. Relative radioactivity, due to ¹³¹I, of iodine in some of the equipment units and in the environment, Case 1.

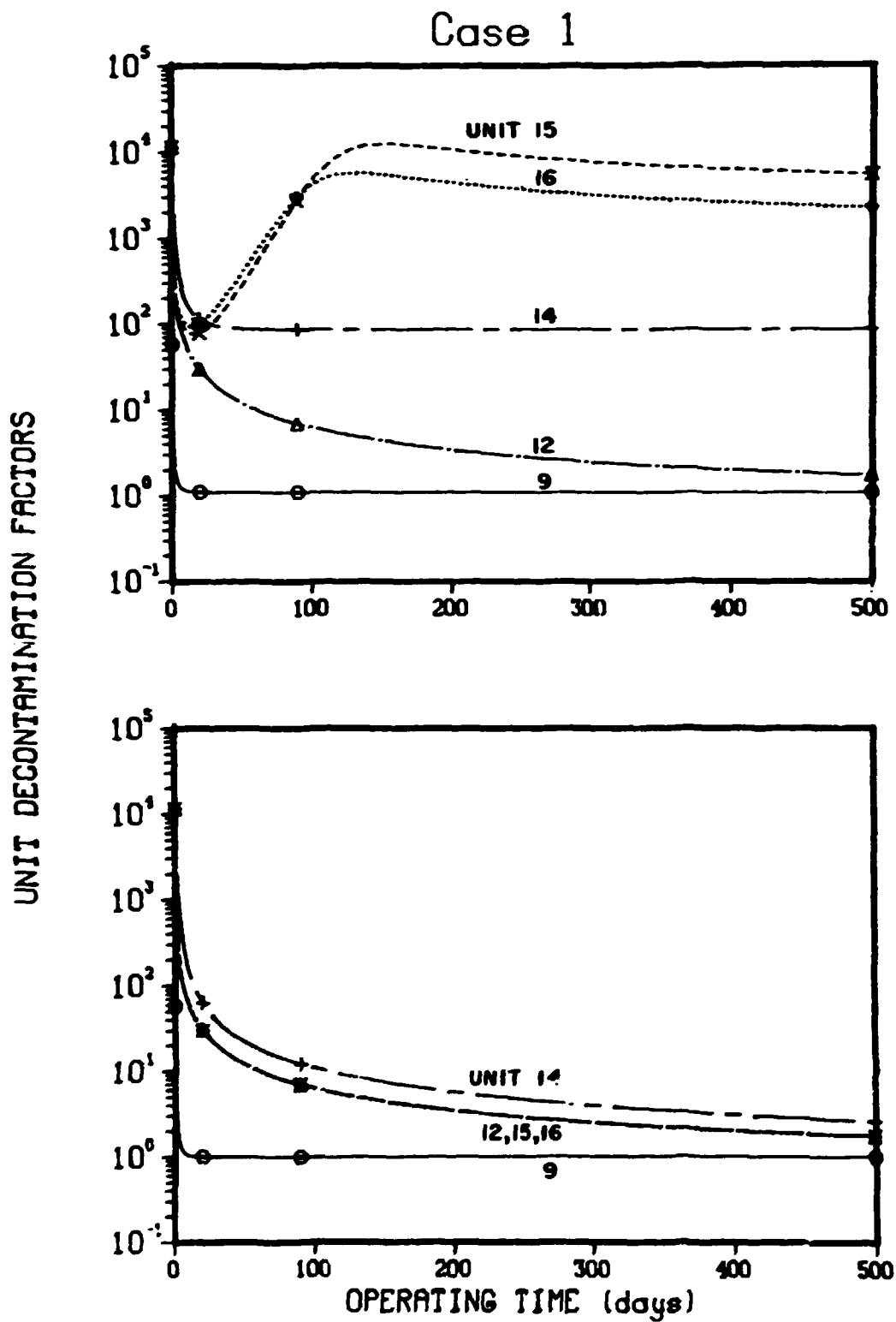


Fig. 6. Calculated time variation of decontamination factors of five process units, Case 1.

Case 2

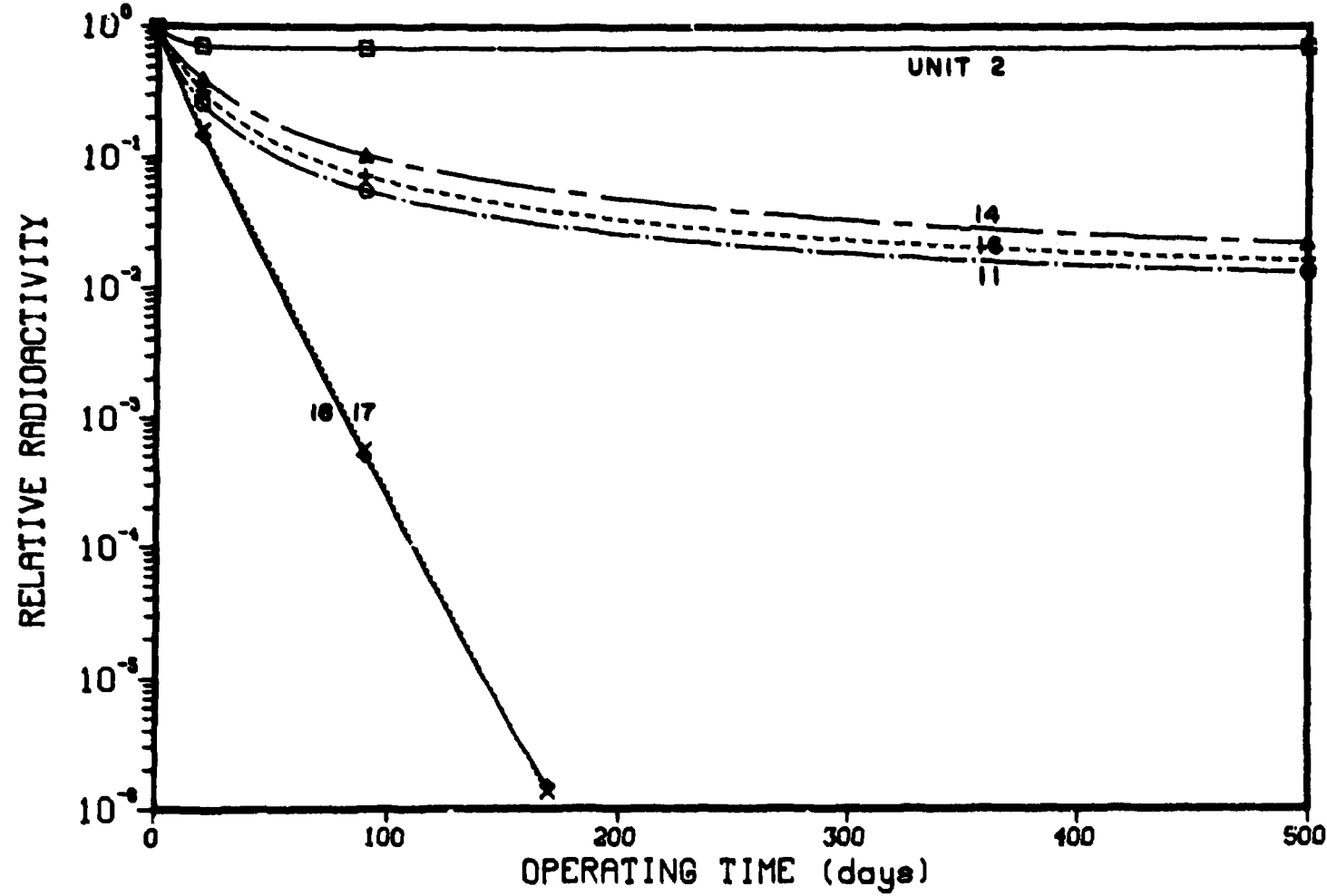


Fig. 7. Relative radioactivity, due to ¹³¹I, of iodine in some of the equipment units and in the environment, Case 2.

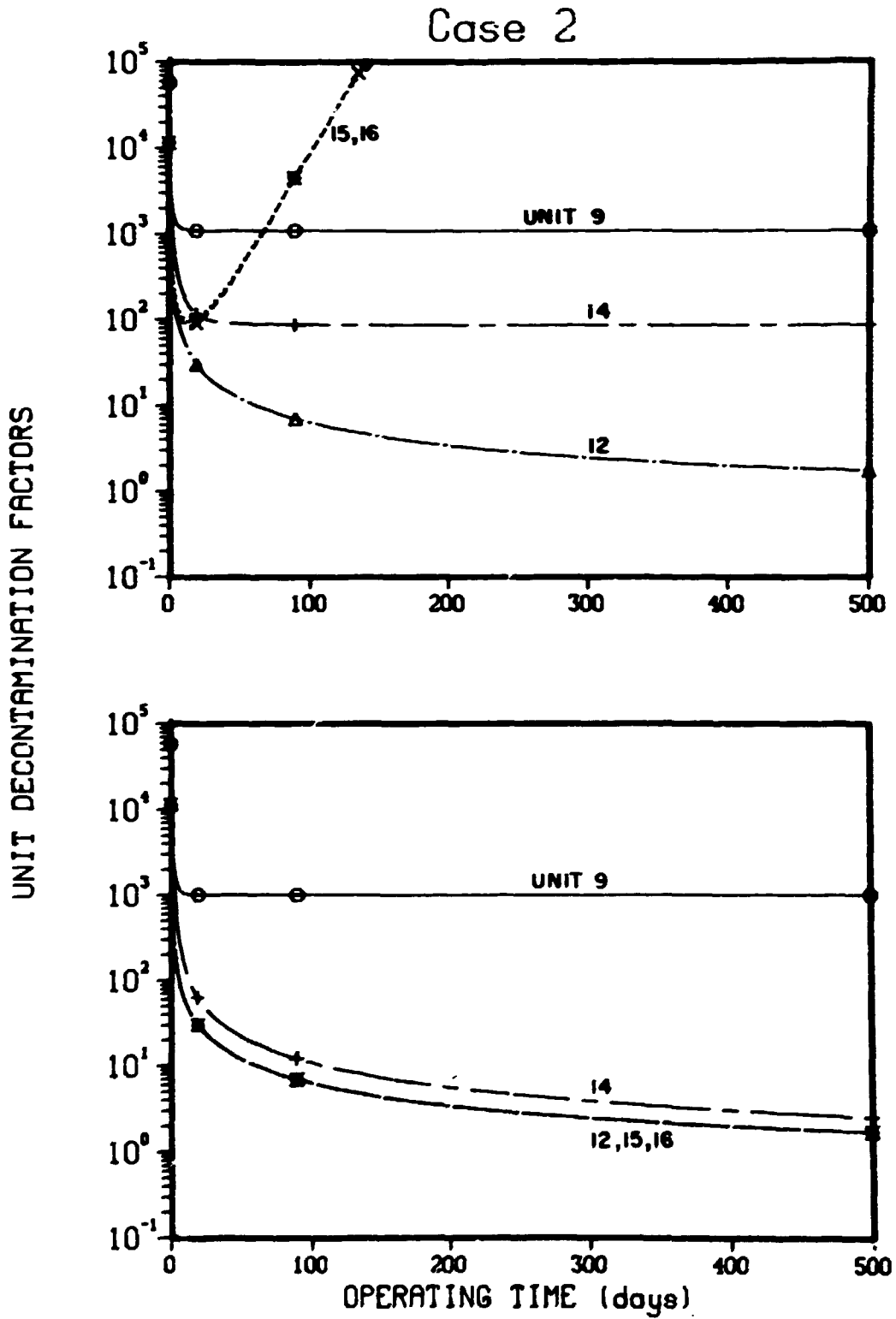


Fig. 8. Calculated time variation of decontamination factors of five process units, Case 2.

Liquid and Gasborne Streams - Case 2

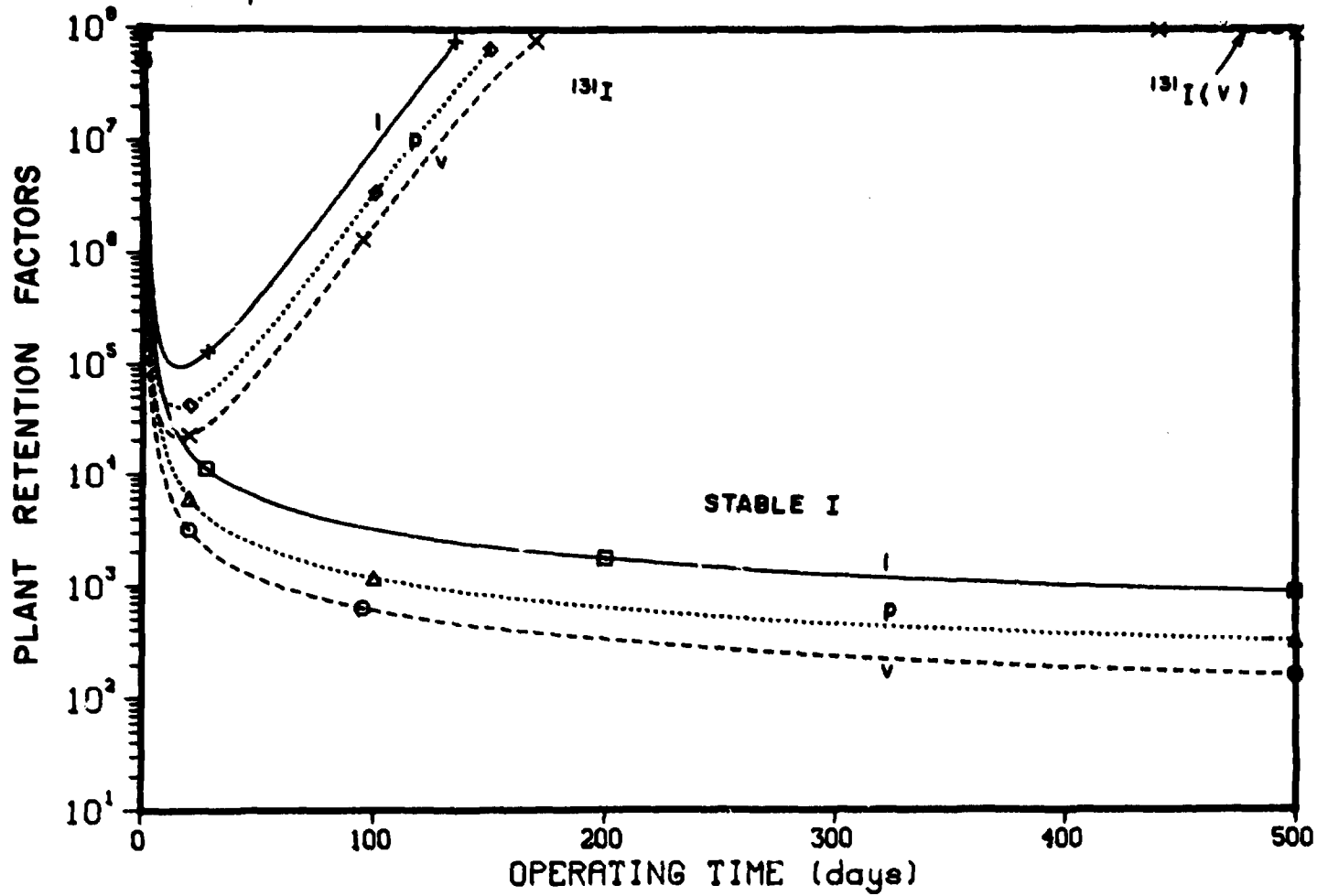


Fig. 9. Plant retention factors for total iodine and ^{131}I in liquid (l) and vapor (v) streams and for the composite streams (p), Case 2.

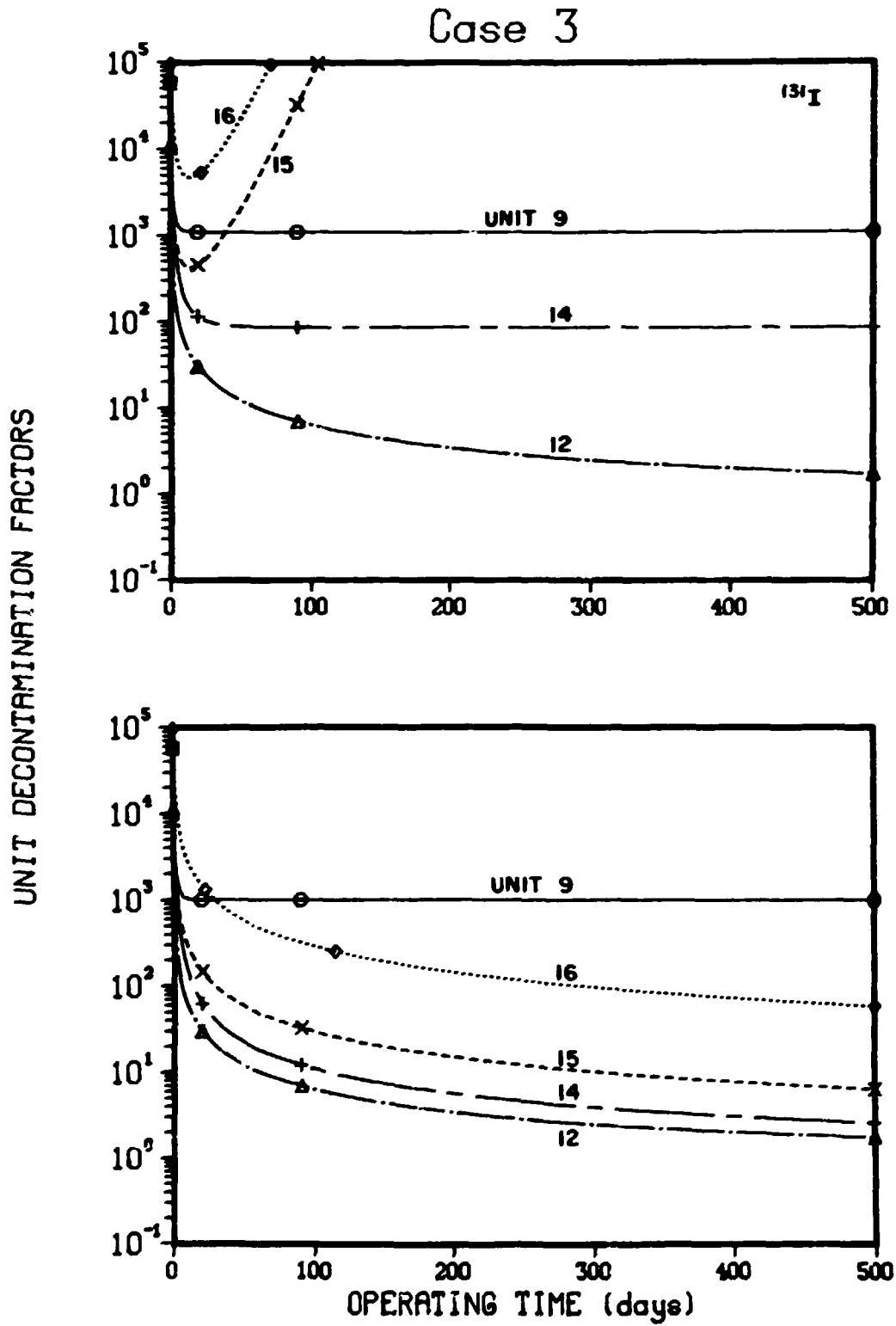


Fig. 10. Calculated time variation of decontamination factors of five process units, Case 3.

TOTAL IODINE INVENTORIES - Case 4

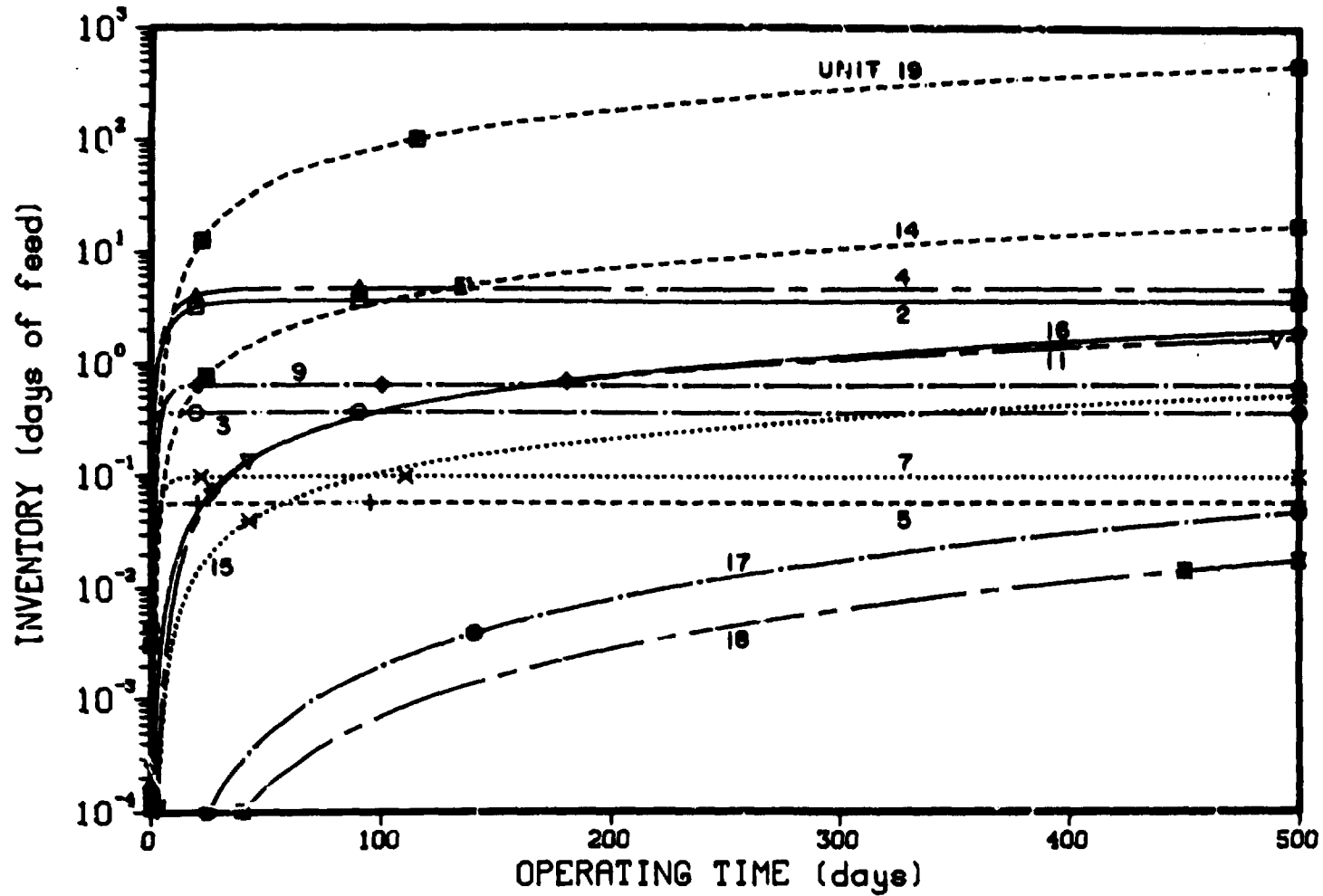


Fig. 11. Increase in inventories of total iodine in plant equipment and in the environment (units 17 and 18 of Fig. 1), Case 4.

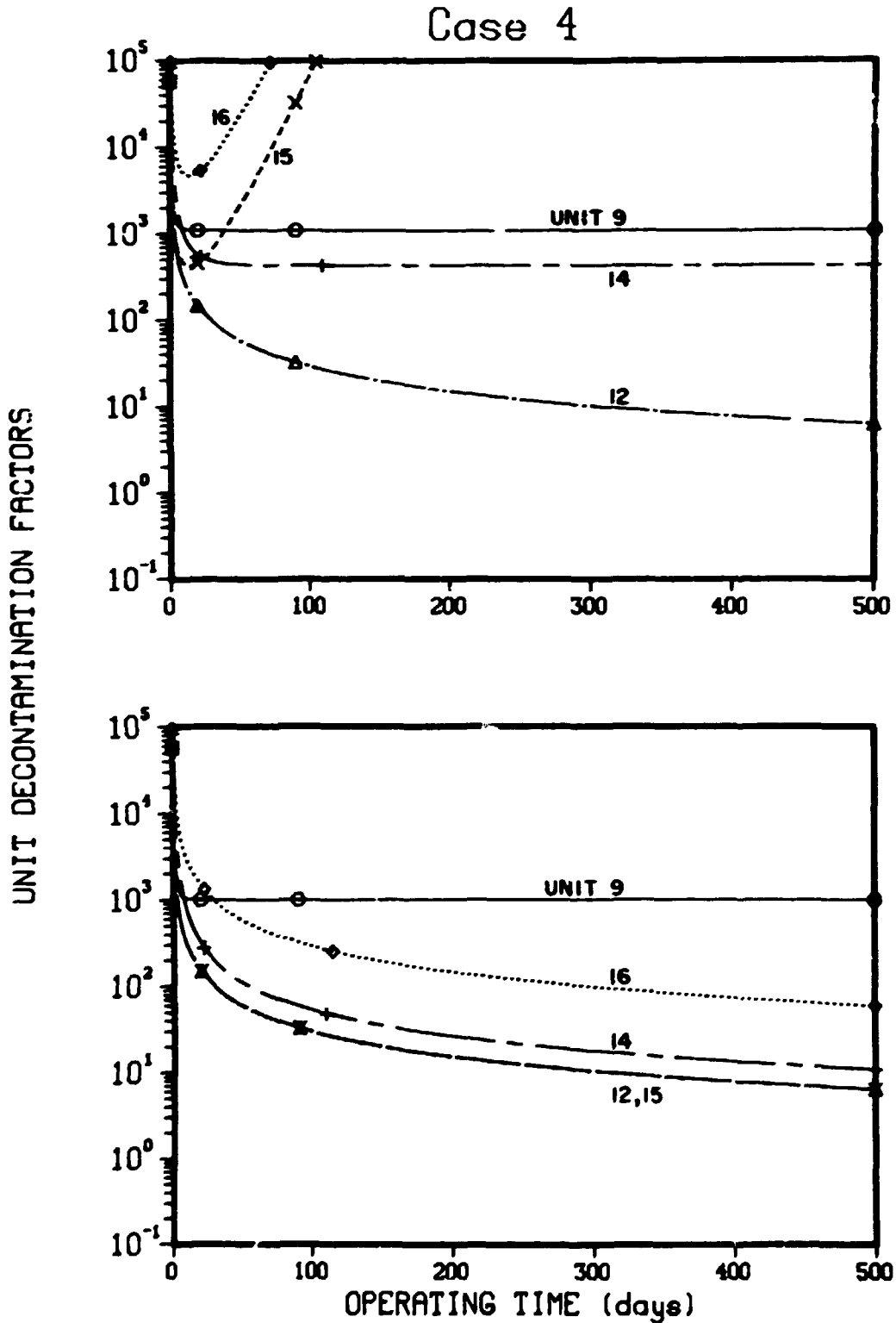


Fig. 12. Calculated time variation of decontamination factors of five process units, Case 4.

Table 2. Values of parameters used in some case studies^a

Parameter ^b	Value of parameter for Case			
	1	2 ^c	3 ^d	4 ^e
Q0001(1)	1.			
Q0001(2)	1.0 D-7			
A1	6.67D-1			
DF2	1.0 D+2			
A3	9.			
DF4	1.0 D+2			
A51	4.0 D-2			
A52	6.0 D-2			
DF7	3.			
DF8	4.			
A91	1.	1.0D-3		
DF10	1.0 D+2			
A13	0.75			
RECYCL	2.16D-3			1.0D-3
HLVENT	1.0 D-3			2.0D-4
$\tau_{1/2}$	8.05			
TENMAX(1)	1.0 D-1			
TENMAX(2)	6.3			
TENMAX(3)	5.0 D-1			
TENMAX(4)	6.3			
TENMAX(5)	1.			
TENMAX(6) ^b	1.0 D+6			
TENMAX(7)	2.			
TENMAX(8)	5.			
TENMAX(9)	2.			
TENMAX(10)	5.			
TENMAX(11)	1.0 D+6			
TENMAX(12)	4.0 D+2			2.0D+3
TENMAX(13)	1.			
TENMAX(14)	1.0 D+6			
TENMAX(15)	4.0 D+2		2.0D+3	
TENMAX(16)	4.0 D+2		2.0D+4	

^aBeyond Case 1, only changed parameters are shown. Each change applies to all subsequent case calculations.

^bTENMAX(6) is actually not used in the model since unit 6 (solvent purification) is assumed to be a permanent sink for iodine.

^cCas. 2 corresponds to the discharge of 99.9% of the iodine collected in unit 9 to unit 19, where the iodine is permanently isolated.

^dCase 3 corresponds to increasing the capacities of units 15 and 16 until their time constants are 2000 days (5.5 years) and 20,000 days (55 years), respectively.

^eCase 4 corresponds to reducing rates of sparging HLW (unit 14) and MLW (unit 11) storage tanks and increasing capacity of unit 12.

because of the very large value, $1.00+6$ days, assigned to them. By assigning large values to these parameters, it is apparent that the corresponding values $\Lambda(11)$ and $\Lambda(14)$ of Eq. (23) will be very small and, therefore, that $S(11)$ and $S(14)$ of Eq. (22) will be nearly zero. Thus, a large value of $TENMAX(K)$ mathematically corresponds to a very large capacity of a unit for retaining iodine, or to the escape of very little iodine from the unit. The units of interest here are as follows: (1) the MLW storage tank (unit 11), and (2) the HLW storage tank (unit 14). There is nothing unique about the assignment of $1.00+6$ days of iodine feed since any value greater than $\sim 1.00+4$ would adequately represent a very large iodine storage capacity. If the value of $TENMAX(14)$ is in the range of tens to hundreds of days, then unit 14 can be considered equivalent to a HLW solidification system from which all contained iodine is returned to the main process as flow Q1402.

Liquid and gasborne plant RFs for both total iodine and for ^{131}I , shown in Figs. 4 and 9, are defined as:

$$RF = \frac{\text{Rate at which element or nuclide enters the plant in the designated stream}}{\text{Rate at which element or nuclide leaves the plant in the designated stream}} \quad (33)$$

Unit DFs shown in Figs. 6, 8, 10, and 12 are defined for total iodine and for ^{131}I as:

$$DF = \frac{\text{Rate at which element or nuclide enters the unit}}{\text{Rate at which element or nuclide leaves the unit}} \quad (34)$$

Many aspects of Figs. 2 to 6, Case 1, require minimal discussion when the various curves are viewed in terms of Fig. 1. For example, steady state flow of iodine is achieved within less than 20 days of the start-up of a new plant in the following streams (as expected from the input data of Table 2): Q0102 and Q0103 from the graphite burner or voloxidizer; Q0305 from dissolver to solvent extraction system; Q0502, Q0506, and Q0507 from the solvent extraction system; and Q0713 and Q0714 from the HLW evaporator. However, steady state is not achieved for iodine flow from the MLW evaporator to the MLW storage tank, Q1011, nor for iodine flows Q0209, Q0409, Q1112, Q1202, or Q1402.

Plant RFs in Fig. 4 are defined as follows:

$$RF(\ell) = Q0103/Q150E ,$$

$$RF(v) = Q0102/Q160E ,$$

and

$$RF(p) = (Q0102+Q0103)/(Q150E+Q160E) .$$

The subscripts ℓ , v , and p correspond to liquid stream, gasborne stream, and plant composite, respectively. Here, the subscripts 1 (for total iodine) and 2 (for ^{131}I) have not been included in the flow terms for brevity. With these definitions and with numerical examples, it is easy to show that the value of $RF(p)$ is less than the larger value of either $RF(\ell)$ and $RF(v)$ but greater than the smaller of these.

Figures 4, 6, 8 to 10, and 12 show reversals of CFs and DFs for ^{131}I that are readily explained. As described in ref. 7, the DF for ^{131}I exceeds that for stable iodine and ^{129}I by an amount that depends on the extent of isotopic exchange, the holdup time during which radioactive decay can occur, the extent of iodine recycle, and the sorber operation time. In the present report, complete isotopic exchange has been assumed. The ratio $DF(^{131}\text{I})/DF(\text{equipment})$, where $DF(\text{equipment})$ applies to stable ^{127}I or to long-lived ^{129}I , is shown for one set of conditions in Fig. 13 (taken from Fig. 6b of ref. 7). The parameters of this two-unit system are shown in Fig. 13. As can be seen, the ratio of DFs will be 1.0 only if the degree of isotopic exchange is 0.0; for all values of fractional isotopic exchange greater than 0.0, there will be an initial increase in the ratio $DF(^{131}\text{I})/DF(\text{equipment})$, followed by a decrease. For the parameters used to obtain Fig. 13, the ratio ceases to increase after ~ 100 days. This figure is based on a constant feed rate of ^{131}I and stable iodine; the increase in the ratio of DFs corresponds to the increase shown in Figs. 4, 6, 8 to 10, and 12 starting after ~ 10 days of operation of the model plant of this report.

The decrease in the RF or DF of ^{131}I that is shown for the first 10 days in Figs. 4, 6, 8 to 10, and 12 does not appear in Fig. 13 because of differences in initial flow conditions. Thus, Fig. 13 is based

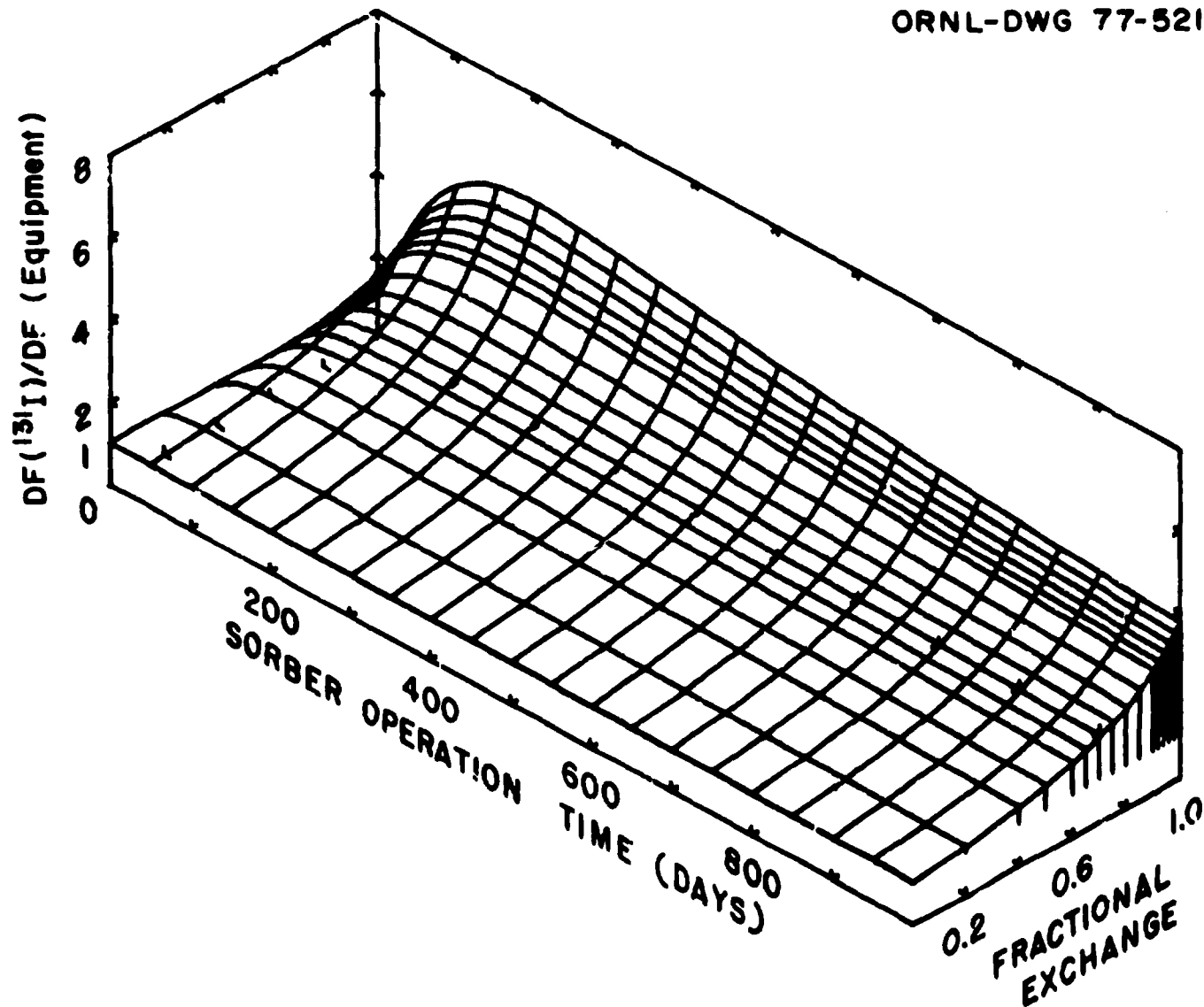


Fig. 13. Effects of time, recycle, and fractional exchange on relative decontamination factors for ^{131}I . $\text{DF}(\text{equipment}) = 20$, $\text{TENMAX} = 60$ days, $R = \text{RECYCL} = 1 \times 10^{-3}$ (from ref. 7).

on a constant flow of ^{131}I and stable iodine into the system; by contrast, the flows of radioactive and stable iodine into units 15 and 16 are initially zero, but these flows increase rapidly. The flow of stable iodine to unit 15, $Q0815(1)$, parallels that of $Q0810(1)$, and the flow of stable iodine to unit 16, $Q0216(1)$, parallels that of $Q0209(1)$ (Fig. 2). Mathematically, the first reversals in Figs. 4, 6, 8 to 10, and 12 occur as a result of the differences:

$$[Q0815(2)-T(15)], \text{ from Eq. (A-28),}$$

and

$$[Q0216(2)-T(16)], \text{ from Eq. (A-22) .}$$

Initially, the terms $Q0815(2)$ and $Q0216(2)$ of ^{131}I flow into units 15 and 16 dominate the terms $T(15)$ and $T(16)$, which are the decay rates λ_{n15} and λ_{n16} of ^{131}I in these units. However, as a result of isotopic exchange and long holdup times, the terms $T(15)$ and $T(16)$ increase faster than the flow terms $Q0815(2)$ and $Q0216(2)$. These changes lead to reversals in DFs for ^{131}I .

The second reversals in the RFs and DFs of ^{131}I are due to a reduction in the residual capacity (an approach to saturation) of units 15 and 16. In an actual plant, these units would be replaced or they might initially be considerably larger than those corresponding to Case 1 of this report (Figs. 4 and 6). Such an increase is shown in Cases 3 and 4 (Figs. 10 and 12) wherein the variables $TENMAX(15)$ and $TENMAX(16)$ were increased to 2000 days (5.5 years) and 20,000 days (55 years), respectively. This value for $TENMAX(16)$ implies that the silver-exchanged zeolite unit 16 would not need to be replaced during the 30- to 40-year life of the fuel reprocessing plant.

The permanent removal of 99.9% of the iodine reaching unit 9 by discharge from units 2 and 4 through fixation in unit 19 produces a significant increase in plant CFs, as shown by a comparison of Figs. 4 and 9. However, there are other important factors, such as the rates of purging or sparging units 11 and 14. These rates are reduced in Case 4.

For the purpose of modelling the time-dependent flow of iodine through a particular nuclear fuel reprocessing plant, it would be more efficient to include only those equipment units actually contained in the plant. For example, the Barnwell plant does not contain units 1, 8, and 15 of Fig. 1; hence, elimination of the equations for these units would simplify the computer calculations. However, some equipment units in Fig. 1 can be "deleted" (in a process sense) by the appropriate choice of time constants. For example, units 8, 10, and 12 can be deleted by decreasing their time constants (TENMAX) to 0.01, 0.01, and 3 days, respectively, from the values 5, 5, and 400 days used in generating the Case 1 plots of Figs. 2 to 6. Gross reduction of a time constant [e.g., reducing TENMAX(12) to 0.001 days] can lead to numerical instabilities, including the values of ^{131}I flows becoming negative after periods corresponding to days or weeks of plant operation. This effect has not been investigated in much detail; it is, however, associated with differences between numbers being very close to 0.0.

5. DISCUSSION AND CONCLUSIONS

Many experimental data are needed in order to determine the time-dependent flows and inventories of total iodine and ^{131}I in a fuel reprocessing plant. These include the 13 parameters listed in Table 1 and rate constant λ to calculate the 15 fractions $S(K)$ described by the first-order time constants TENMAX(K) in Sect. 2.* All of these parameters are needed if the fuel reprocessing plant actually contains all of the units shown in Fig. 1. Excluding the values of Q0001(1) and Q0001(2), which are well known, the parameters of Table 1 are probably uncertain by factors ranging from 1.25 to 10, or larger. Hence, numerical values pertaining to the examples discussed in Sect. 4 are more qualitative than quantitative. Overall, calculated total-iodine RFs, Fig. 4, are consistent with those assumed or calculated in the steady state models used in refs. 4 and 5. However, a few aspects do need further comment. First, plant

*TENMAX(6) is not actually used in model calculations because unit 6 is considered to be a permanent sink for iodine.

RFs for ^{131}I will exceed those for stable iodine by values in the range of 10^4 (Fig. 4), including Case 1. Studies in which the capacities of units 15 and 16 are increased to many years, perhaps as long as the lifetime of the plant (Cases 3 and 4), show that the DF value of ^{131}I will exceed that of stable iodine by 10^6 or more. Such factors are considerably higher than those used in refs. 4 and 5. Second, no studies described here are based on parameters that would lead to the "near zero" release described by Yarbrow, Harrington, and Joy;¹⁷ however, only a few of the parameters listed in Tables 1 and 2 would need to be changed to produce this near zero release. Changes that would be required are as follows: (1) increase A3 from 9 to 99 or 99.5, corresponding to the evolution of 99 or 99.5% of iodine from the dissolver instead of the 90% used in all studies reported here; (2) increase DF2 to 10^3 or 10^4 , corresponding to the use of the Iodox process¹¹ or to the operation of a $\text{Hg}(\text{NO}_3)_2\text{-HNO}_3$ scrubber solution at a significantly higher efficiency than has been assumed thus far;^{4,5} (3) increase A91 to 10^4 or 10^6 from the value 10^3 used in this report, corresponding to the more complete discharge of iodine from unit 9 for permanent isolation in unit 19. Finally, it should be noted that the case studies reported here and modifications that could lead to still greater retention of iodine are all based on the assumption that the process equipment containing iodine does not leak. Any iodine leaking from process equipment would enter the cell-ventilation off-gas equipment, thereby partially invalidating the model plant defined in Fig. 1.

It is difficult to assess the accuracy of the assumption of first-order kinetics, Eq. (22), as it applies to a process unit for iodine removal. The volumetric change in each unit due to iodine removal (Fig. 1) is so small that liquid and sol. phase processes may be considered to occur at constant volume. For example, an iodine flow⁷ of ~ 10 g-atoms/day in an LWR fuel reprocessing plant having a capacity of 5 metric tons (MT) of (uranium + plutonium) per day corresponds, at a maximum concentration of 300 g uranium/liter, to a maximum of 0.0005 M I, or 0.00025 M I_2 . Removal of all of this iodine would produce a trivial change in the volume of the dissolver solution in unit 3 of Fig. 1. As a second

example, sorption of iodine on a 26% silver-exchanged sodium zeolite¹⁸ will probably not exceed 25 to 50 mg of iodine per milliliter of zeolite before the zeolite is replaced; this corresponds to less than a 1% change in the volume of the zeolite.

Without going into details, such as those found in ref. 19, the nearly-constant-volume process of iodine removal in each of the many units of an LWR fuel reprocessing plant would appear to be fairly accurately represented by first-order kinetics. This comment applies to the following potential process units: (1) a batch dissolver and (2) a continuous dissolver, the solvent extraction system, or distillation units which nearly correspond to back-mix flow reactors. Sorption on silver zeolite or on ion exchange resin are probably more accurately represented by the plug-flow processes.¹⁹

The present model of iodine transport and chemical reaction or physical retention is capable of being accommodated to any experimental data that may be obtained in the future. For example, no difficulty would be encountered if any, or all, of the rate processes were found to require replacement of first-order kinetics by more complicated processes. Each replacement of a first-order kinetic equation, as in Eq. (22), would be simple from the standpoint of computer programming. Such replacement would produce small changes in the curves of Figs. 2 to 12 but could not produce major changes.

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7. APPENDICES

APPENDIX A. EVALUATION OF IODINE FLOW RATES

As noted in Sect. 2, the model of this report is based on the assumptions that (1) each equipment unit through which iodine flows has a definable maximum capacity (holdup) for iodine and (2) the rate at which iodine leaves the unit is proportional to the degree of saturation of this maximum and to the rate at which iodine enters the unit. For unit 1, the model therefore corresponds to:

$$DER(1,L) = [Q0001(1)-T(1)]*[1-S(1)] , \quad (A-1)$$

or to the equivalent form

$$Q0102(L)+Q0103(L) = [Q0001(1)-T(1)]*S(1) . \quad (A-2)$$

In Table 1, the experimental datum A1 provides the equation:

$$Q0102(L)-A1*Q0103(L) = 0 . \quad (A-3)$$

From Eqs. (A-2) and (A-3) we thus obtain

$$Q0103(L) = [Q0001(L)-T(1)]*S(1)/(1+A1) , \quad (A-4)$$

and from Eq. (A-3) we obtain

$$Q0102(L) = A1*Q0103(L) . \quad (A-5)$$

Equations corresponding to other units are as follows:

Unit 2:

$$Q0209(L)+Q0216(L)-Q0402(L)*S(2)-Q0502(L)*S(2) = \\ [Q0102(L)+Q1202(L)+Q1402(L)-T(2)]*S(2) \quad (A-6)$$

and

$$Q0209(L)+Q0216(L)*(1-DF2) = 0 . \quad (A-7)$$

Unit 3:

$$Q0304(L)+Q0305(L)-Q1303(L)*S(3) = [Q0103(L)-T(3)]*S(3) \quad (A-8)$$

and

$$Q0304(L) - Q0305(L) * A3 = 0 \quad (A-9)$$

Unit 4:

$$Q0402(L) + Q0409(L) - Q0304(L) * S(4) = -S(4) * T(4) \quad (A-10)$$

and

$$Q0402(L) * (DF4-1) - Q0409(L) = 0 \quad (A-11)$$

Unit 5:

$$-Q0305(L) * S(5) + Q0502(L) + Q0506(L) + Q0507(L) = -S(5) * T(5) \quad (A-12)$$

$$Q0502(L) * (1-A51) - Q0506(L) * A51 - Q0507(L) * A51 = 0 \quad (A-13)$$

and

$$-Q0502(L) * A52 + Q0506(L) * (1-A52) - Q0507(L) * A52 = 0 \quad (A-14)$$

Unit 6:

This is the solvent purification unit; the equations refer to the net accumulation of iodine. Thus, this unit is treated as a permanent sink for iodine, which is lost only by radioactive decay.

Unit 7:

$$-Q0507(L) * S(7) + Q0713(L) + Q0714(L) = -S(7) * T(7) \quad (A-15)$$

and

$$Q0713(L) * (DF7-1) - Q0714(L) = 0 \quad (A-16)$$

Unit 8:

$$Q0810(L) + Q0815(L) - Q1008(L) * S(8) - Q1308(L) * S(8) = -S(8) * T(8) \quad (A-17)$$

and

$$-Q0810(L) + Q0815(L) * (DF8-1) = 0 \quad (A-18)$$

Unit 9:

$$-Q0209(L) * S(9) - Q0409(L) * S(9) + Q0910(L) + Q0919(L) = -S(9) * T(9) \quad (A-19)$$

and

$$-Q0910(L) * (1-A91) + Q0919(L) * A91 = 0 \quad (A-20)$$

Unit 10:

$$-Q0810(L)*S(10)-Q0910(L)*S(10)+Q1008(L)+Q1011(L) = -S(10)*T(10) \quad (A-21)$$

and

$$Q1008(L)*(DF10-1)-Q1011(L) = 0 \quad (A-22)$$

Unit 11:

This is the MLW storage tank system. Iodine leaves this unit only if it is purged, or sparged, at a rate

$$Q112(1) = R*EN(11,L) \quad (A-23)$$

where R is the sparge rate in units of day^{-1} and EN(11,L) is the inventory of component L in unit 11.

Unit 12:

$$\begin{aligned} Q1202(L) &= [Q1112(L)-T(12)]*S(12) \\ &= [R*EN(11,L)-T(12)]*S(12) \end{aligned} \quad (A-24)$$

Unit 13:

$$-Q0713(L)*S(13)+Q1303(L)+Q1308(L) = -S(13)*T(13) \quad (A-25)$$

and

$$Q1303(L)*(A13-1)+Q1308(L)*A13 = 0 \quad (A-26)$$

Unit 14:

This is a permanent HLW storage system that is vented to the off-gas system. The rate of venting is considered to be operator-controlled according to

$$Q1402(L) = HLVENT*EN(14,L) \quad (A-27)$$

where HLVENT is a vent rate (similar to R), in units of day^{-1} , and EN(14,L) is the inventory of component L in unit 14.

Unit 15:

$$Q150E(L) = [Q0815(L)-T(15)]*S(15) \quad (A-28)$$

Unit 16:

$$Q160E(L) = [Q0216(L)-T(16)]*S(16) \quad (A-29)$$

Unit 17:

This is the environment, which receives iodine due to the vaporization of iodine-containing excess water from the plant. This is a permanent sink for iodine, which is lost only by radioactive decay.

Unit 18:

This is the environment, which receives iodine from the off-gas system. This, also, is a permanent sink for iodine, which is lost only by radioactive decay.

Unit 19:

This is a permanent sink corresponding to any method of permanent removal of iodine from the system.

Equations (A-4), (A-5), (A-23), (A-24), and (A-27) can be solved for values of $Q0102(L)$, $Q0103(L)$, $Q1202(L)$, and $Q1402(L)$. These four flow rates plus $Q0001(L)$ are then used in the 18 by 18 matrix Eq. (29) to solve for $Q0209(L)$, $Q0216(L)$, $Q0304(L)$, $Q0305(L)$, $Q0402(L)$, $Q0409(L)$, $Q0502(L)$, $Q0506(L)$, $Q0507(L)$, $Q0713(L)$, $Q0714(L)$, $Q0810(L)$, $Q0815(L)$, $Q0910(L)$, $Q1008(L)$, $Q1011(L)$, $Q1303(L)$, and $Q1308(L)$. Three of these 18 flow rates, namely $Q0815(L)$, $Q0216(L)$, and $Q0910(L)$, are then used to solve for the three remaining flows $Q150E(L)$, $Q160E(L)$, and $Q0919(L)$.

APPENDIX B. DEFINITIONS AND VALUES OF PARAMETERS

The values of $TENMAX(K)$ defined in this report are not the same as those that would normally be determined in laboratory experiments. In the latter, a constant flow of iodine in a liquid or gas stream would be used to introduce this element into some type of sorber; in a fuel reprocessing plant, this inlet flow would continually increase until the preceding unit(s) was(were) saturated with iodine. Thus, for example, the constant used for the iodine-sorber unit 2 (Fig. 1) will be influenced by the buildup of iodine in units 1, 4, 5, 12, and 14. Individual values of $TENMAX(K)$ are described as follows.

- $TENMAX(1)$ = the holdup-time constant of iodine in a head-end voloxidizer or graphite burner. It is presumed to be on the order of a few hours, or ~ 0.1 days, in units consistent with those used in this report.
- $TENMAX(2)$ = the holdup-time constant of iodine in the primary iodine sorber in the off-gas system. If unit 2 is a $Hg(NO_3)_2-HNO_3$ scrubber and if this solution is continuously partially replaced, then the equivalent holdup time may be ~ 1 week. Concentrated nitric acid of the Iodox process¹¹ or an efficient metal-exchanged zeolite might provide holdup times significantly longer.
- $TENMAX(3)$ = the holdup-time constant of iodine in the unit in which UO_2 , PuO_2 , ThO_2 , etc., of the nuclear fuel, are dissolved. This time is in the order of a few tenths of a day.
- $TENMAX(4)$ = the holdup-time constant of iodine in any iodine-retention unit in the dissolver off-gas stream. This may be as long as 8 days if a $Hg(NO_3)_2-HNO_3$ scrubber solution is used and as short as 0.01 days if no such unit is used.
- $TENMAX(5)$ = the holdup-time constant of iodine in the solvent extraction system. This is probably in the order of a few tenths to 0.5 days.

- TENMAX(6)** = the holdup-time constant of iodine in the solvent recovery (repurification) system. Iodine arriving at this unit, which may be a Na_2CO_3 - NaOH scrubber-washer system, is not expected to return to the solvent extraction system. For this reason, there is no flow from unit 6 [see Fig. 1 and Eq. (6)], and **TENMAX(6)** is not actually used in the model; it is assigned a nonzero value, such as 1.D+6 days, for convenience.
- TENMAX(7)** = the holdup-time constant of iodine in a HLW aqueous waste evaporator. This is presumed to be ~1 to 3 days.
- TENMAX(8)** = the holdup-time constant of iodine in the iodine-removal partial evaporator. It is considered to require a small number of days to approach steady state operation.
- TENMAX(9)** = the holdup-time constant of iodine in what may be a neutralization unit from which iodine may be discharged for permanent isolation. The retention time will probably be only a few days.
- TENMAX(10)** = the holdup-time constant of iodine in the MLW evaporator. If such a unit is used, the time constant may be on the order of a few days.
- TENMAX(11)** = the holdup-time constant of iodine in the MLW storage tank. The holdup-time is assumed to be very long and set equal to 1.D+6 days in this study.
- TENMAX(12)** = the holdup-time constant of iodine in any unit through which sparge gas from the MLW storage tank passes before reaching the off-gas system. This time will be short (0.01 to 1 day) if no such unit is used and may range from many days to many years if, for example, a silver-exchanged zeolite is used.
- TENMAX(13)** = the holdup-time constant of iodine in the nitric-acid recovery system. This will be on the order of a few days.

- TENMAX(14)** = the holdup-time constant of iodine in the HLW storage system (probably very long unless this system is considered to include waste solidification). A value of 1.D+6 is used in this study.
- TENMAX(15)** = the holdup-time constant of iodine in the iodine-removal ion exchange. This constant will range from hundreds of days to many years when such a unit is used.
- TENMAX(16)** = the holdup-time constant of iodine in the silver-exchanged zeolite of the off-gas system. It will range from hundreds of days to many years.

APPENDIX C. DECOMPOSITION OF MATRIX EQUATION (29)

The matrix Eq. (29) can be decomposed into a 9 by 9, a 4 by 4, and a 5 by 5 matrix, shown in Eqs. (C-1) to (C-3). To take advantage of this decomposition, these equations must be solved in the order listed since flows Q0304 and Q0502 determined in Eq. (C-1) are used in Eq. (C-2); flow Q1308 from Eq. (C-1) and flows Q0209 and Q0409 from Eq. (C-2) are used in Eq. (C-3). Several time checks show that a computer program based on solving these three smaller matrices executes and prints ~30% faster than a program based on the 18 by 18 matrix of Eq. (29). However, the program listed in this appendix is based on Eq. (29).

Samples of calculations shown in Figs. 2 to 12 pertain to an initially "new" plant; that is, one not exposed to iodine before the zero time of these plots. The computer programs are not so restricted; instead, SUBROUTINE FRP requires that initial inventories be provided as input. All input values of initial inventories were set to zero in this example.

1	-A3											0
1	1											(0103-T3)*S3
		1-A51	-A51	-A51								0
		-A52	1-A52	-A52								0
	-S5	1	1	1								-S5*T5
				-S7	1	1						-S7*T7
					DF7-1	-1						0
						-S3						-S13*T13
												0

*

00304	00306	00302	00508	00607	00713	00714	01303	01308
-------	-------	-------	-------	-------	-------	-------	-------	-------

=

0	(0103-T3)*S3	0	0	-S5*T5	-S7*T7	0	-S13*T13	0
---	--------------	---	---	--------	--------	---	----------	---

(C-L)

$$\begin{bmatrix} 1 & 1-DF2 & & & \\ & 1 & -S2 & & \\ & & & 1 & 1 \\ & & & & DF4-1 & -1 \end{bmatrix} * \begin{bmatrix} Q0208 \\ Q0216 \\ Q0402 \\ Q0409 \end{bmatrix} = \begin{bmatrix} 0 \\ (Q0102 + Q0502 + Q1202 + Q1402 - T2) * S2 \\ (Q0304 - T4) * S4 \\ 0 \end{bmatrix} \tag{C-2}$$

$$\begin{bmatrix} -1 & DF8-1 & & & \\ & 1 & & & \\ & & & -S8 & \\ & & & & \frac{1}{A91} \\ & -S10 & & 1 & 1 \\ & & & & DF10-1 & -1 \end{bmatrix} * \begin{bmatrix} Q0810 \\ Q0815 \\ Q0910 \\ Q1008 \\ Q1011 \end{bmatrix} = \begin{bmatrix} 0 \\ (Q1308 - T8) * S8 \\ (Q0209 + Q0409 - T9) * S9 \\ -S10 * T10 \\ 0 \end{bmatrix} \tag{C-3}$$

```

COMMON/TAFEL/WTIB,WTOD,WTOP,WTOC
WTIB = 9
WTOD = 6
WTOP = 7
WTOC = 26
CALL LISTIT(05,WTOP,WTIB)
BRIND WTIB
CALL FOP
STOP 1357
END

```

```

SUBROUTINE HORN (TIME, EW, DER)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION EW(19,2), DER(19,2)
DIMENSION PHITD(19)
DIMENSION QXIT(16,2)

```

```

COMMON/DECAY/A 1, A3, A51, A52, A91, A13, DP2, DP4, DP7, DP8,
1 DP10, EL, EMAX(16), RLVENT, QRATIO, RATIO(20),
2 RECTCL, IDEX
COMMON/LBCOM1/LAMBDA(16), G(16), S(16), T(20)
COMMON/MATRIX/A(10,10), SA(10,10), B(10,2), I(10,2)
COMMON/QCQOO, Q0001(2), Q0102(2), Q0103(2), Q0209(2), Q0216(2),
1 Q0304(2), Q0305(2), Q0402(2), Q0409(2), Q0502(2),
2 Q0506(2), Q0507(2), Q0713(2), Q0714(2), Q0810(2),
3 Q0815(2), Q0910(2), Q0919(2), Q1000(2), Q1011(2),
4 Q1112(2), Q1202(2), Q1303(2), Q1308(2), Q1402(2),
5 Q150E(2), Q160E(2)

```

```

DATA ONE/1.000/
*****

```

C
C
C
C
C

```

CALCULATION OF THE KINETIC FACTORS, S(I), GOES HERE, WHERE
S(I) = FRACTION OF A UNIT'S CAPACITY TO SORB IODINE THAT HAS
ALREADY BEEN USED.

```

```

DO 102 I = 1, 19
IF (I .GT. 16) GO TO 02
IF (S(I) .EQ. ONE) GO TO 02
72 S(I) = ONE - DER(- LAMBDA(I) * TIME)
82 T(I) = EL * EW(I,2)
102 CONTINUE

```

C
C
C
C

```

END CALCULATION OF S(I)

```

```

*****

```

```

DO 502 F = 1, 2
QXIT(1,K) = (Q0001(K) - T(1)) * S(1)
Q0103(K) = QXIT(1,K) * G(1)
Q0102(K) = Q0103(K) * A1
Q1112(K) = RECTCL * EW(11,K)
Q1202(K) = Q1112(K) * S(12)
Q1402(K) = RLVENT * EW(14,K)
DO 152 I = 1, 10
DO 102 J = 1, 10
A(I,J) = SA(I,J)
102 CONTINUE
B(I,K) = 0.0
152 CONTINUE
A(2,5) = - S(2)
A(2,7) = - S(2)
A(5,17) = - S(3)
A(5,3) = - S(4)
A(9,4) = - S(5)
A(10,9) = - S(7)
A(13,15) = - S(8)
A(13,18) = - S(8)
A(14,1) = - S(9)
A(14,6) = - S(9)
A(15,12) = - S(10)
A(15,16) = - S(10)
A(17,10) = - S(13)
B(2,K) = (Q0102(K) + Q1202(K) + Q1402(K) - T(2)) * S(2)
B(3,K) = (Q0103(K) - T(3)) * S(3)
B(5,K) = - S(4) * T(4)
B(9,K) = - S(5) * T(5)
B(10,K) = - S(7) * T(7)
B(13,K) = - S(8) * T(8)
B(14,K) = - S(9) * T(9)
B(15,K) = - S(10) * T(10)
B(17,K) = - S(13) * T(13)
202 CALL DNATEQ (A, B(1,K), 10, 1, 10)
DO 212 J = 1, 10
I(J,K) = B(J,K)
212 CONTINUE
Q0209(K) = B(1,K)
Q0216(K) = B(2,K)
Q0304(K) = B(3,K)
Q0305(K) = B(4,K)

```

```

Q0402(K) = B(5,K)
Q0409(K) = B(6,K)
Q0502(K) = B(7,K)
Q0506(K) = B(8,K)
Q0507(K) = B(9,K)
Q0713(K) = B(10,K)
Q0714(K) = B(11,K)
Q0810(K) = B(12,K)
Q0815(K) = B(13,K)
Q0910(K) = B(14,K)
Q0919(K) = Q0910(K) * (IN(14,14) - ONE)
Q1000(K) = B(15,K)
Q1011(K) = B(16,K)
Q1303(K) = B(17,K)
Q1300(K) = B(18,K)
Q1502(K) = (Q0815(K) - T(15)) * S(15)
Q1602(K) = (Q0816(K) - T(16)) * S(16)
052 Q00(1,K) = (Q0001(K) - T(1)) * (ONE - S(1))
Q00(2,T) = (Q0102(K) + Q0402(K) + Q0502(K) + Q1202(K) +
Q1402(K) - T(2)) * (ONE - S(2))
Q00(3,K) = (Q0103(K) + Q1303(K) - T(3)) * (ONE - S(3))
Q00(4,K) = (Q0104(K) - T(4)) * (ONE - S(4))
Q00(5,K) = (Q0305(K) - T(5)) * (ONE - S(5))
Q00(6,K) = Q0506(K) - T(6)
Q00(7,K) = (Q0507(K) - T(7)) * (ONE - S(7))
Q00(8,K) = (Q1000(K) + Q1300(K) - T(8)) * (ONE - S(8))
Q00(9,K) = (Q0209(K) + Q0409(K) - T(9)) * (ONE - S(9))
Q00(10,K) = (Q0010(K) + Q0910(K) - T(10)) * (ONE - S(10))
Q00(11,K) = Q1011(K) - T(11) - Q1112(K)
Q00(12,K) = Q1112(K) - T(12) - Q1202(K)
Q00(13,K) = (Q0713(K) - T(13)) * (ONE - S(13))
Q00(14,K) = Q0714(K) - T(14) - Q1402(K)
Q00(15,K) = (Q0815(K) - T(15)) * (ONE - S(15))
Q00(16,K) = (Q0816(K) - T(16)) * (ONE - S(16))
Q00(17,K) = Q1502(K) - T(17)
Q00(18,K) = Q1602(K) - T(18)
Q00(19,K) = Q0919(K) - T(19)
    
```

302 CONTINUE
RETURN
END

```

SUBROUTINE PBP
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION CAPAC(16)
DIMENSION DELT(10)
DIMENSION EW(19,2), EWO(19,2), EWRATO(250,19)
DIMENSION RL(50), RS(10)
DIMENSION Q(250,20)
DIMENSION R(250,20)
DIMENSION ST(250), SUBR1(250), SUBR31(250)
DIMENSION TERNAX(10)
DIMENSION Y(30), YI(250,30)
COMMON/DECAT/A1, A2, A3, A51, A52, A91, A13, DP1, DP2, DP7, DP8,
1 DP10, EL, EMAX(16), ELLEFT, QRATIO, RATIO(20),
2 RECTCL, IINDEX
COMMON/LDCONT/ALANRA(16), G(16), S(16), T(20)
COMMON/MATRIX/A(10,10), SA(10,10), B(10,2), X(10,2)
COMMON/QCQOC/Q0001(2), Q0102(2), Q0103(2), Q0209(2), Q0216(2),
1 Q0304(2), Q0305(2), Q0402(2), Q0409(2), Q0502(2),
2 Q0506(2), Q0507(2), Q0713(2), Q0714(2), Q0810(2),
3 Q0815(2), Q0816(2), Q0910(2), Q0919(2), Q1000(2), Q1011(2),
4 Q1112(2), Q1202(2), Q1303(2), Q1300(2), Q1402(2),
5 Q1502(2), Q1602(2)
COMMON/TAPES/VI,NO,RP,RTTC
COMMON/UNITDE/DF9(250,2), DF12(250,2), DF13(250,2), DF15(250,2),
1 DF16(250,2)
REAL*8 CAPAC, DP9, DP12, DP14, DP15, DP16, EWRATO, Q, R
REAL*8 ST, SUBR1, SUBR31, TEL, TEIP, TEZP, YI
EQUIVALENCE (EW(1,1), Y(1))
EXTERNAL EQUA
    
```

C
C
C
C
C
C
C
C
C
C
C
C
C
C
C

THIS PROGRAM ANALYZES THE FLOWS OF IODINE ISOTOPES IN A NUCLEAR-FUEL REPROCESSING PLANT THAT HAS A HEAD-END TREATMENT, SUCH AS VOLatilIZATION FOR LWR AND LWRFB FUELS OR DOWNTAKE FOR ETC FUELS, FLOW SOLVENT EXTRACTION AND BASIC-STREAM HANDLING PROCESSES SIMILAR TO THOSE AT THE DREHVELL PLANT OF 1975.

```

I          = 1 REFERS TO TOTAL IODINE
           = 2 REFERS TO I-131

Q0001(I)   = RATE OF FLOW INTO UNIT 1
Q0102(I)   = RATE OF FLOW FROM UNIT 1 TO UNIT 2
Q0103(I)   = RATE OF FLOW FROM UNIT 1 TO UNIT 3
    
```

C Q0200 (I) = RATE OF FLOW FROM UNIT 2 TO UNIT 9
 C Q0216 (I) = RATE OF FLOW FROM UNIT 2 TO UNIT 16
 C Q0300 (I) = RATE OF FLOW FROM UNIT 3 TO UNIT 0
 C Q0305 (I) = RATE OF FLOW FROM UNIT 3 TO UNIT 5
 C Q0402 (I) = RATE OF FLOW FROM UNIT 0 TO UNIT 2
 C Q0409 (I) = RATE OF FLOW FROM UNIT 0 TO UNIT 9
 C Q0502 (I) = RATE OF FLOW FROM UNIT 5 TO UNIT 2
 C Q0506 (I) = RATE OF FLOW FROM UNIT 5 TO UNIT 6
 C Q0507 (I) = RATE OF FLOW FROM UNIT 5 TO UNIT 7
 C Q0713 (I) = RATE OF FLOW FROM UNIT 7 TO UNIT 13
 C Q0716 (I) = RATE OF FLOW FROM UNIT 7 TO UNIT 16
 C Q0810 (I) = RATE OF FLOW FROM UNIT 8 TO UNIT 10
 C Q0815 (I) = RATE OF FLOW FROM UNIT 8 TO UNIT 15
 C Q0910 (I) = RATE OF FLOW FROM UNIT 9 TO UNIT 10
 C Q0919 (I) = RATE OF FLOW FROM UNIT 9 TO UNIT 19
 C Q1000 (I) = RATE OF FLOW FROM UNIT 10 TO UNIT 0
 C Q1011 (I) = RATE OF FLOW FROM UNIT 10 TO UNIT 11
 C Q1112 (I) = RATE OF FLOW FROM UNIT 11 TO UNIT 12
 C = RATE OF RECYCLE OF IODINE FROM THE CONCENTRATED
 C MISCELLANEOUS WASTE TANK
 C = 2.760-03 PER DAY IF THE PUMP RATE AT UNIT 7 IS
 C 300. CPM PER 3.0005 GALLONS, IF THE DISTRIBUTION
 C COEFFICIENT, DEFINED AS
 C $(C_{CONC. I2 IN SOLUTION}) / (C_{CONC. I2 IN VAPOR})$,
 C EQUALS 5000. FOR THE ALKALINE SOLUTION IN THE
 C CONCENTRATED MISCELLANEOUS WASTE TANK, AND IF
 C I2 EQUILIBRIUM EXISTS BETWEEN LIQUID AND VAPOR.
 C
 C = ONE OF THE LEAST WELL-KNOWN VARIABLES OF THE SYSTEM
 C Q1202 (I) = RATE OF FLOW FROM UNIT 12 TO UNIT 2
 C Q1303 (I) = RATE OF FLOW FROM UNIT 13 TO UNIT 3
 C Q1308 (I) = RATE OF FLOW FROM UNIT 13 TO UNIT 8
 C Q1402 (I) = RATE OF FLOW FROM UNIT 14 TO UNIT 2
 C Q1502 (I) = RATE OF FLOW FROM UNIT 15 TO ENVIRONMENT
 C Q1602 (I) = RATE OF FLOW FROM UNIT 16 TO ENVIRONMENT
 C
 C UNIT 1 = A VOLCANIZES OR GRAPHITE SUPPER
 C UNIT 2 = $HG(NO_3)_2 \cdot HNO_3$, OR IO_2O_4 , OR A IODITE,
 C THE PRIMARY IODINE SCRUBBER IN THE OFF-GAS STREAM
 C UNIT 3 = THE DISSOLVER
 C UNIT 4 = $HG(NO_3)_2 \cdot HNO_3$, OR IO_2O_4 , OR A IODITE,
 C AN IODINE SCRUBBER IN THE DISSOLVED OFF-GAS LINE
 C UNIT 5 = THE SOLVENT-EXTRACTION SYSTEM
 C UNIT 6 = THE SOLVENT-PURIFICATION SYSTEM
 C UNIT 7 = HIGH LEVEL WASTE EVAPORATOR
 C UNIT 8 = IODINE-REMOVAL PARTIAL EVAPORATOR
 C UNIT 9 = NEUTRALIZATION TANK OR IODINE-WASTE SCRUBBER
 C UNIT 10 = MISCELLANEOUS LIQUID WASTE EVAPORATOR
 C UNIT 11 = CONCENTRATED MISCELLANEOUS LIQUID-WASTE
 C STORAGE TANK
 C UNIT 12 = IODINE SCRUBBER IN THE RECYCLE LINE
 C UNIT 13 = HNO_3 RECOVERY SYSTEM

- UNIT 14 = HIGH LEVEL WASTE STORAGE SYSTEM
 UNIT 15 = IODINE-REMOVAL ION EXCHANGE
 UNIT 16 = A SILVER ZEOLITE SORBER UNIT,
 THE SECONDARY IODINE SORBER IN THE OFF-GAS STREAM
 UNIT 17 = THE ENVIRONMENT VIA VAPORIZED WATER
 UNIT 18 = THE ENVIRONMENT VIA THE OFF-GAS
 UNIT 19 = AN IODINE FIXATION UNIT

- FLOW RATZS = DIMENSIONLESS (NORMALIZED BY DIVIDING ACTUAL FLOW
 RATE BY RATE OF FLOW INTO UNIT 1)
 TIME = DAYS, A CONVERSION SINCE THE HALF-LIFE OF
 I-131 IS 8.05 DAYS
 EL = DECAY CONSTANT
 = $0.67(2.) / 8.05$ PER DAY FOR I-131
 HALFIP = HALF-LIFE OF I-131
 = 8.05 DAYS

 INPUT PARAMETERS -----

- A1 = $Q0102(1) / Q0103(1)$
 = IODINE VAPORIZED / IODINE REMAINING IN FUEL
 IN THE VOLICIDIZER OF GRAPHITE BURNER, UNIT 1
 = 0.67 (APPROX) FOR THE GRAPHITE BURNER
 = 2. (APPROX) FOR THE VOLICIDIZER
 A3 = $Q0304(1) / Q0305(1)$
 = IODINE VAPORIZED / IODINE REMAINING IN SOLUTION
 IN THE DISSOLVER
 = 9. (APPROX) IN NORMAL OPERATIONS
 = 199. (APPROX) WHEN IODINE EVOLUTION IS USED
 A51 = $Q0502(1) / (Q0502(1) + Q0506(1) + Q0507(1))$
 = FRACTION OF IODINE LEAVING THE SOLVENT EXTRACTION
 SYSTEM THAT REPORTS TO THE OFF-GAS (PISTLE AS
 ORGANIC IODIDES)
 A52 = $Q0506(1) / (Q0502(1) + Q0506(1) + Q0507(1))$
 = FRACTION OF IODINE LEAVING THE SOLVENT EXTRACTION
 SYSTEM THAT REPORTS TO THE SOLVENT PURIFICATION
 SYSTEM
 A91 = $Q0910(1) / (Q0910(1) + Q0919(1))$
 = FRACTION OF IODINE LEAVING THE IODINE-COLLECTION
 UNIT 9 THAT IS RECYCLED TO THE PLANT RATHER THAN
 BEING FIRED FOR DEWATERING ISOLATION
 A13 = $Q1303(1) / (Q1303(1) + Q1308(1))$
 = EQUIPMENT DF ACROSS THE HNO3 RECOVERY SYSTEM
 DF2 = $(Q0209(1) + Q0216(1)) / Q0216(1)$
 = EQUIPMENT DF OF THE PRIMARY UNIT 2 IN THE OFF-GAS
 STREAM
 = 100. FOR H₂O(2)-HNO₃ AND CADMIUM ZEOLITE
 = 1000. FOR IODINE
 DF4 = $(Q0402(1) + Q0409(1)) / Q0402(1)$
 = EQUIPMENT DF OF THE IODINE SORBER IN THE DISSOLVER
 OFF-GAS STREAM
 DF7 = $(Q0713(1) + Q0714(1)) / Q0713(1)$
 = EQUIPMENT DF ACROSS THE H₂O EVAPORATOR
 DF8 = $(Q0814(1) + Q0815(1)) / Q0815(1)$
 = EQUIPMENT DF ACROSS THE IODINE-REMOVAL PARTIAL
 EVAPORATOR
 = 4.
 DF10 = $(Q1008(1) + Q1011(1)) / Q1008(1)$
 = EQUIPMENT DF ACROSS THE MISCELLANEOUS LIQUID
 WASTE EVAPORATOR
 T(J) = HOLDUP TIME IN UNIT J, DAYS
 P(1) = DERIV (EN(1,1)) / DT

```

C      F(2)      = DERIV (E(2,1)) / DT
C      F(3)      = DERIV (E(3,1)) / DT
C      F(10)     = DERIV (E(1,2)) / DT
C      F(17)     = DERIV (E(2,2)) / DT
C      F(10)     = DERIV (E(3,2)) / DT
C
C      Y(1)      = E(1,1) * ELEMENTAL TOTAL IN UNIT 1
C      Y(2)      = E(2,1) * ELEMENTAL TOTAL IN UNIT 2
C      Y(3)      = E(3,1) * ELEMENTAL TOTAL IN UNIT 3
C      Y(10)     = E(1,2) * SHORT-LIVED ISOTOPE IN UNIT 1
C      Y(17)     = E(2,2) * SHORT-LIVED ISOTOPE IN UNIT 2
C      Y(10)     = E(3,2) * SHORT-LIVED ISOTOPE IN UNIT 3
C
C-----
C      CALL IBIISL
C      NBOXES = 16
C      ONE = 1.000
C      41 READ (BI,9001) ACCURC, DEL, YMAX, WE
C      READ (BI,9011) NSUB, TIMEB, (NS(I), DELT(I), I = 1,NSUB)
C      51 READ (BI,9051) DP2, DP4, DP7, DP8, DP10
C      IF (DP2 - ONE) 1001, 401, 61
C      61 READ (BI,9051) A1, A3, A51, A52, A91, A13
C      READ (BI,9051) NAPLIF, ELVENT, QRATIO, RECYCL
C      READ (BI,9051) (TENDAT(I), I = 1,NBOXES)
C      READ (BI,9051) (E00(I,1), I = 1,19)
C      READ (BI,9051) (E00(I,2), I = 1,19)
C      EL = DLOG(2.000) / NAPLIF
C      C(1) = ONE / (ONE + A1)
C      L = 1
C      LOWER = 1
C      LUPPER = NS(L)
C      Q0001(1) = ONE
C      Q0001(2) = QRATIO * Q0001(1)
C      RECYC = ONE / QRATIO
C      T1 = 0.0
C      TEL = EL
C      REZF = QRATIO / EL
C      DO 151 I = 1, 19
C         Y(I) = E00(I,1)
C         Y(I+19) = E00(I,2)
C 151 CONTINUE
C      SA(1,2) = ONE - DP2
C      SA(2,1) = ONE
C      SA(3,4) = - A3
C      SA(4,3) = ONE
C      SA(5,6) = ONE
C      SA(6,5) = DP4 - ONE
C      SA(6,6) = - ONE
C      SA(7,7) = ONE - A51
C      SA(7,8) = - A51
C      SA(7,9) = - A51
C      SA(8,7) = - A52
C      SA(8,8) = ONE - A52
C      SA(8,9) = - A52
C      SA(9,7) = ONE
C      SA(9,8) = ONE
C      SA(10,11) = ONE
C      SA(11,10) = DP7 - ONE
C      SA(11,11) = - ONE
C      SA(12,12) = - ONE
C      SA(12,13) = DP8 - ONE
C      SA(13,12) = ONE
C      SA(14,14) = ONE / A91
C      SA(15,14) = ONE
C      SA(16,15) = DP10 - ONE
C      SA(16,16) = - ONE
C      SA(17,18) = ONE
C      SA(18,17) = A13 - ONE
C      SA(18,18) = A13
C      DO 171 I = 1,NBOXES
C         ALARDA(I) = DLOG(2.000) / TENDAT(I)
C         QATIO(I) = QRATIO
C 171 CONTINUE
C      RATIO(17) = QRATIO
C      RATIO(18) = QRATIO
C      RATIO(19) = QRATIO
C 201 DO 301 J = LOWER, LUPPER
C      T0 = T1
C      T1 = T1 + DELT(L)
C      CALL KOTIL(T0, T1, Y, WE, DEL, ACCURC, INAT, EQQA)
C      DP9(J,1) = (Q0209(1) + Q0409(1)) / Q0910(1)
C      DP9(J,2) = (Q0209(2) + Q0409(2)) / Q0910(2)
C      DP12(J,1) = Q1112(1) / Q1202(1)
C      DP12(J,2) = Q1112(2) / Q1202(2)
C      DP14(J,1) = Q0714(1) / Q1402(1)
C      DP14(J,2) = Q0714(2) / Q1402(2)
C      DP15(J,1) = Q0815(1) / Q1502(1)
C      DP15(J,2) = Q0815(2) / Q1502(2)

```



```

DP16(J, 1) = Q0216(1) / Q160E(1)
DP16(J, 2) = Q0216(2) / Q160E(2)
Q(J, 1) = Q0001(1)
Q(J, 2) = Q0102(1)
Q(J, 3) = Q0103(1)
Q(J, 4) = Q0204(1)
Q(J, 5) = Q0210(1)
Q(J, 6) = Q0300(1)
Q(J, 7) = Q0305(1)
Q(J, 8) = Q0402(1)
Q(J, 9) = Q0409(1)
Q(J, 10) = Q0502(1)
Q(J, 11) = Q0506(1)
Q(J, 12) = Q0507(1)
Q(J, 13) = Q0713(1)
Q(J, 14) = Q0710(1)
Q(J, 15) = Q0010(1)
Q(J, 16) = Q0015(1)
Q(J, 17) = Q0910(1)
Q(J, 18) = Q0919(1)
Q(J, 19) = Q1000(1)
Q(J, 20) = Q1011(1)
Q(J, 21) = Q1112(1)
Q(J, 22) = Q1202(1)
Q(J, 23) = Q1303(1)
Q(J, 24) = Q1300(1)
Q(J, 25) = Q1402(1)
Q(J, 26) = Q150E(1)
Q(J, 27) = Q160E(1)
R(J, 1) = Q0001(2)
R(J, 2) = Q0102(2)
R(J, 3) = Q0103(2)
R(J, 4) = Q0204(2)
R(J, 5) = Q0210(2)
R(J, 6) = Q0300(2)
R(J, 7) = Q0305(2)
R(J, 8) = Q0402(2)
R(J, 9) = Q0409(2)
R(J, 10) = Q0502(2)
R(J, 11) = Q0506(2)
R(J, 12) = Q0507(2)
R(J, 13) = Q0713(2)
R(J, 14) = Q0710(2)
R(J, 15) = Q0010(2)
R(J, 16) = Q0015(2)
R(J, 17) = Q0910(2)
R(J, 18) = Q0919(2)
R(J, 19) = Q1000(2)
R(J, 20) = Q1011(2)
R(J, 21) = Q1112(2)
R(J, 22) = Q1202(2)
R(J, 23) = Q1303(2)
R(J, 24) = Q1300(2)
R(J, 25) = Q1402(2)
R(J, 26) = Q150E(2)
R(J, 27) = Q160E(2)
ST(J) = T1
SUMER(J) = 0.0
SUME31(J) = 0.0
DO 251 JJ = 1, 19
  SUMER(J) = SUMER(J) + R(JJ, 1)
  SUME31(J) = SUME31(J) + R(JJ, 2)
  IF (T(JJ)) 221, 221, 231
221  RATIO(JJ) = Q/RATIO
  GO TO 201
231  RATIO(JJ) = R(JJ, 2) / R(JJ, 1)
241  ERRATO(J, JJ) = RATIO(JJ) - RECIP
251  CONTINUE
DO 201 JL = 1, 30
  Y(J, JL) = Y(JL)
201  CONTINUE
301  CONTINUE
IF (L - NSEC) 311, 401, 401
311  L = L + 1
  LOWER = LUPPER + 1
  LUPPER = LUPPER + N1(L)
  IF (LUPPER .LE. 250) GO TO 201
401  CONTINUE
  CALL OUTPT(ERRATO, Q, R, ST, SUMER, SUME31, Y, TEL, TE2P,
  1  LUPPER, N1)
  CALL PLOT12(ERRATO, Q, R, ST, Y, LUPPER)
  GO TO 01
1001  WRITE (NO, 9101)
9001  FORMAT (2E10.0, 2I5)
9011  FORMAT (5(I5, E10.0))
9051  FORMAT (8E10.0)
9101  FORMAT (1R1)
  RETURN

```

END

```

SUBROUTINE INISH.
IMPLICIT REAL*8 (A-H,O-Z)
COMMON/LBCOM1/ALAMDA(16), C(16), S(16), T(20)
COMMON/WRITEX/A(70,79), SA(10,10), B(10,2), X(10,2)
COMMON/QCCOR/Q(50)
OVR = 1.0D0
DO 113 I = 1,50
  Q(I) = 0.
113 CONTINUE
DO 123 I = 1,16
  S(I) = 0.
123 CONTINUE
DO 143 I = 1,10
  DO 133 J = 1,10
    SA(I,J) = 0.
133 CONTINUE
  B(I,1) = 0.
  B(I,2) = 0.
  X(I,1) = 0.
  X(I,2) = 0.
  SA(I,I) = OVR
143 CONTINUE
RETURN
END

SUBROUTINE OUTPUT(ENRATO, J, R, ST, SUMER, SURE31, YI, TEL, TEIP,
1 LUPPER, HL)
DIMENSION ENRATO(250,19)
DIMENSION HL(50)
DIMENSION Q(250,20)
DIMENSION P(250,20)
DIMENSION ST(250)
DIMENSION SUMER(250), SURE31(250)
DIMENSION YI(250,30)
COMMON/TAPES/NI,NO,NP,NTTC
IUP = LUPPER / 50
JUP = 50 * IUP
IF (JUP - LUPPER) 011, 021, 021
011 IUP = IUP + 1
021 IUP1 = IUP - 1
HL(IUP) = LUPPER - IUP1 + 50
IF (IUP .LE. 1) GO TO 001
DO 031 LK = 1,IUP1
  HL(LK) = 50
031 CONTINUE
001 JL1 = - 09
  JL2 = 0
  DO 061 I = 1, IUP
    WRITE (NO,9107)
    WRITE (NO,9401)
    WRITE (NO,9457)
    JL1 = JL1 + 50
    JL2 = JL2 + HL(I)
    DO 051 N = JL1, JL2
      WRITE (NO,9701) ST(N), (Q(M,N), NR = 1,10)
051 CONTINUE
061 CONTINUE
  JL1 = - 09
  JL2 = 0
  DO 541 I = 1, IUP
    WRITE (NO,9107)
    WRITE (NO,9411)
    WRITE (NO,9457)
    JL1 = JL1 + 50
    JL2 = JL2 + HL(I)
    DO 081 N = JL1, JL2
      WRITE (NO,9901) ST(N), (Q(M,N), NR = 11,20)
081 CONTINUE
041 CONTINUE
  JL1 = - 09
  JL2 = 0
  DO 521 I = 1, IUP
    WRITE (NO,9107)
    WRITE (NO,9421)
    WRITE (NO,9457)
    JL1 = JL1 + 50
    JL2 = JL2 + HL(I)
    DO 511 N = JL1, JL2
      WRITE (NO,9901) ST(N), (Q(M,N), NR = 21,27)
511 CONTINUE
521 CONTINUE
  JL1 = - 09
  JL2 = 0
  DO 561 I = 1, IUP

```

```

WRITE (NO,910)
WRITE (NO,906)
WRITE (NO,905)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 551 N = JL1, JL2
WRITE (NO,990) ST(N), (P(N,MM), MM = 1,10)
551 CONTINUE
561 CONTINUE
JL1 = - 49
JL2 = 0
DO 601 I = 1, IUP
WRITE (NO,910)
WRITE (NO,907)
WRITE (NO,905)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 501 N = JL1, JL2
WRITE (NO,990) ST(N), (R(N,MM), MM = 11,20)
601 CONTINUE
601 CONTINUE
JL1 = - 49
JL2 = 0
DO 621 I = 1, IUP
WRITE (NO,910)
WRITE (NO,908)
WRITE (NO,905)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 611 N = JL1, JL2
WRITE (NO,990) ST(N), (R(N,MM), MM = 21,27)
611 CONTINUE
621 CONTINUE
JL1 = - 49
JL2 = 0
DO 721 I = 1, IUP
WRITE (NO,910)
WRITE (NO,950)
WRITE (NO,951)
WRITE (NO,905)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 711 N = JL1, JL2
WRITE (NO,990) ST(N), (R(N,MM), MM = 1,10)
711 CONTINUE
721 CONTINUE
JL1 = - 49
JL2 = 0
DO 741 I = 1, IUP
WRITE (NO,910)
WRITE (NO,950)
WRITE (NO,952)
WRITE (NO,905)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 731 N = JL1, JL2
WRITE (NO,990) ST(N), (R(N,MM), MM = 11,19)
731 CONTINUE
741 CONTINUE
JL1 = - 49
JL2 = 0
DO 821 I = 1, IUP
WRITE (NO,910)
WRITE (NO,960)
WRITE (NO,951)
WRITE (NO,905)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 811 N = JL1, JL2
WRITE (NO,990) ST(N), (TY(N,PM), MM = 1,10)
811 CONTINUE
821 CONTINUE
JL1 = - 49
JL2 = 0
DO 841 I = 1, IUP
WRITE (NO,910)
WRITE (NO,960)
WRITE (NO,952)
WRITE (NO,905)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 831 N = JL1, JL2
WRITE (NO,990) ST(N), (TY(N,MM), MM = 11,19), SORER(N)
831 CONTINUE
841 CONTINUE
JL1 = - 49
JL2 = 0
DO 861 I = 1, IUP

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```

WRITE (NO,940)
WRITE (NO,941)
WRITE (NO,951)
WRITE (NO,945)
JL1 = JL1 + 50
JL2 = JL2 + NL(I)
DO 051 B = JL1, JL2
  WRITE (NO,990) ST(N), (TY(N,MM), MM = 20,29)
051 CONTINUE
061 CONTINUE
JL1 = - 49
JL2 = 0
DO 001 I = 1, IUP
  WRITE (NO,940)
  WRITE (NO,941)
  WRITE (NO,952)
  WRITE (NO,945)
  JL1 = JL1 + 50
  JL2 = JL2 + NL(I)
DO 071 B = JL1, JL2
  TEMP = TEMP * (1.0 - EXP(- TEL * ST(N)))
  ARATIC = SUME31(N) / TEMP
  WRITE (NO,990) ST(N), (TY(N,MM), MM = 30,30), ARATIC
071 CONTINUE
001 CONTINUE
9101 FORMAT (1H)
9401 FORMAT (' TIME 0001(1) 00102(1) 00103(1) 00209(1)
1) 00216(1) 00304(1) 00305(1) 00402(1) 00409(1) 0
20502(1) '/')
9411 FORMAT (' TIME 00506(1) 00507(1) 00713(1) 00714(1)
1) 00810(1) 00815(1) 00910(1) 00919(1) 01008(1) 0
21011(1) '/')
9421 FORMAT (' TIME 01112(1) 01202(1) 01303(1) 01304(1)
1) 01402(1) 0150E(1) 0160E(1)
2 '/')
9451 FORMAT (' DAYS '/')
9461 FORMAT (' TIME 0001(2) 00102(2) 00103(2) 00209(2)
1) 00216(2) 00304(2) 00305(2) 00402(2) 00409(2) 0
20502(2) '/')
9471 FORMAT (' TIME 00506(2) 00507(2) 00713(2) 00714(2)
1) 00810(2) 00815(2) 00910(2) 00919(2) 01008(2) 0
21011(2) '/')
9481 FORMAT (' TIME 01112(2) 01202(2) 01303(2) 01304(2)
1) 01402(2) 0150E(2) 0160E(2)
2 '/')
9501 FORMAT (' RELATIVE RADIOACTIVITY = SPECIFIC ACTIVITY AT STATED
1) UNIT / SPECIFIC ACTIVITY OF INLET IODINE
2 '/')
9511 FORMAT (' TIME UNIT 1 UNIT 2 UNIT 3 UNIT 4
1) UNIT 5 UNIT 6 UNIT 7 UNIT 8 UNIT 9
2) UNIT 10 '/')
9521 FORMAT (' TIME UNIT 11 UNIT 12 UNIT 13 UNIT 1
1) UNIT 15 UNIT 16 ENV(L) ENV(W) UNIT 19
2 '/')
9601 FORMAT (' INVENTORY OF TOTAL IODINE '/')
9611 FORMAT (' INVENTORY OF I-131 '/')
9901 FORMAT (2H, F8.2, 1X, 1P10E12.4)
RETURN
END

```

```

SUBROUTINE OUTRC(T, Y, YMAX, YMIN, LMAX)
  DIMENSION D(250), E(250), T(250)
  DIMENSION X(1), Y(1)
  DO 106 I = 1, LMAX
    Z(I) = Y(I)
106 CONTINUE
  IP = 0
206 IA = 0
216 IP = IP + 1
226 IF (IP .GT. LMAX) RETURN
  IF (E(IP) .LE. YMIN .OR. E(IP) .GT. YMAX) GO TO 216
206 IA = IA + 1
  D(IA) = E(IP)
  T(IA) = X(IP)
  LMX = IA
256 IP = IP + 1
266 IF (IP .GT. LMAX) RETURN
276 IF (E(IP) .LE. YMIN .OR. E(IP) .GT. YMAX) GO TO 306
206 IA = IA + 1
  D(IA) = E(IP)
  T(IA) = X(IP)
  LMX = IA
  IF (IP .EQ. LMAX) GO TO 306
  GO TO 256
306 CALL CURVE(T, D, LMX, 100)
  GO TO 206
  END

```



```

IF (NCASE .GE. 10) J = 2
CALL REPLAC(TITLE(1,1), 1, 31, 'L(IQWIB) S(TREMS) - C(ASH) S')
CALL REPLAC(TITLE(1,2), 1, 32, 'G(ASDDBH) S(TREMS) - C(ASH) S')
CALL REPLAC(TITLE(1,3), 1, 46, 'L(IQWIB) M(H) G(ASDDBH) S(TREMS)
1 - C(ASH) S')
CALL REPLAC(TITLE(1,4), 1, 10, 'C(ASH) S')
CALL REPLAC(TITLE(1,5), 1, 37, 'TOTAL IONISE INVERTORIES - C(ASH)
1 S')
CALL REPLAC(TITLE(1,6), 1, 10, 'C(ASH) S')
CALL REPLAC(TITLE(1,7), 29, 3, STB)
CALL REPLAC(TITLE(1,8), 31, 3, STB)
CALL REPLAC(TITLE(1,9), 40, 3, STB)
CALL REPLAC(TITLE(1,10), 0, 3, STB)
CALL REPLAC(TITLE(1,11), 35, 3, STB)
CALL REPLAC(TITLE(1,12), 0, 3, STB)
CALL REPLAC(TITLE(1,13), 32, 4, HEX1)
CALL REPLAC(TITLE(1,14), 30, 4, HEX1)
CALL REPLAC(TITLE(1,15), 47, 4, HEX1)
CALL REPLAC(TITLE(1,16), 11, 4, HEX1)
CALL REPLAC(TITLE(1,17), 30, 4, HEX1)
CALL REPLAC(TITLE(1,18), 11, 4, HEX1)
C
C PLOTTING IS PERFORMED BY USE OF THE DISPLA SYSTEM OF
C INTEGRATED SOFTWARE SYSTEMS COMP.
C
CALL CALCP(0)
C ** CALL BEND1 (IPLOT) LEVEL 0,1
CALL BEND1 (IPLOT)
C ** CALL BASALP ('ALPHABET') LEVEL 1,2,3 P/S
CALL BASALP ('STANDARD')
C ** CALL HIALP ('ALPHABET') LEVEL 1,2,3 P/S
CALL HIALP ('L/CSTO')
C ** CALL GRACE (SPACE) LEVEL 1,2,3 P/S
CALL GRACE (0.)
C ** CALL XINAX LEVEL 1,2,3 P/S
CALL XINAX
C ** CALL PHYSO (MOD, TOO) LEVEL ? P/S
CALL PHYSO (2., 6.)
C ** CALL YAXNG (ANG) LEVEL 1,2,3 P/S
CALL YAXNG (0.)
C ** CALL TITLE (LTITLE, ITITLE, LYNAME, IYNAME,
C ** 1 LYNAME, IYNAME, XAXIS, YAXIS) LEVEL 1
CALL TITLE (TITLE(1,1), 100, 0, 0,
1 M, 1, XAXIS(1), YAXIS(1))
CYCLE = YAXIS(1) / ALOG10 (TRM / YMIN)
C ** CALL YLOG (XOBIG, XSTEP, XOBIG, YCYCLE) LEVEL 2
CALL YLOG (XMIN, XSTEP(1), YMIN, YCYCLE)
C ** CALL XGRAYS (XOBIG, XSTEP, XMAX, XAXIS,
C ** 1 LYNAME, IYNAME, XPOS, YPOS) LEVEL 3
CALL XGRAYS (YMIN, XSTEP(1), XMAX(1), XAXIS(1), 10, 1, 0., 0.)
C ** CALL FRAME LEVEL 2,3
CALL FRAME
105 IV = 3
ICT = 1
115 IS = ICT - 1
C ** CALL NAMEB (ISY) LEVEL 1,2,3 P/S
CALL NAMEB (IS)
CALL OUTNG (ST, Q(1,IV), XMAX, YMIN, 162)
GO TO (125, 135, 145, 155, 165, 205), ICT
125 IV = 4
ICT = 2
CALL CHDDOT
GO TO 115
135 IV = 7
ICT = 3
CALL CHDDB
GO TO 115
145 IV = 9
ICT = 4
CALL DASH
GO TO 115
155 IV = 12
ICT = 5
CALL DOT
GO TO 115
165 IV = 10
ICT = 6
CALL RESET ('DOT')
GO TO 115
205 CONTINUE
CALL ENDG(1)
CALL PHYSO (2., 1.5)
CALL TITLE (0, 0, 0, 0, 10, 1, XAXIS(1), YAXIS(1))
CALL YLOG (XMIN, XSTEP(2), YMIN, YCYCLE)
CALL XGRAYS (YMIN, XSTEP(2), XMAX(2), XAXIS(1),
1 'OPERATING TIME ((DAT5) S', 100, 0., 0.)
CALL FRAME

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```

IV = 15
ICT = 7
215 IS = ICT - 1
CALL SUBRTD(13)
CALL OUTR(GST, 0(1,IV), TRAX, YRIB, LEAD)
ICT6 = IC - 6
GO TO (225, 235, 245, 255) , ICT6
225 IV = 16
ICT = 8
CALL CNDGT
GO TO 215
235 IV = 20
ICT = 9
CALL CNDOSH
GO TO 215
245 IV = 23
ICT = 10
CALL DASH
GO TO 215
255 CONTINUE
CALL XNDG(2)
FLENG = IONES('RELATIVE TUBE FLOW RATE', 100)
TUBE = 6. - 0.5 * FLENG
CALL ADRL(70.)
CALL HESG('RELATIVE IONISE FLOW RATE', 100, - 1.0, TORIG)
CALL DSH('ANGLE')
CALL DSH('DASH')
CALL PSH(1)
CALL PSH(2., 6.)
CALL TITLE('TITLE(1,2), 100, 0, 0,
           ' , 1, IAXIS(1), YAXIS(1))
CALL FLOG(XRIB, ISTEP(1), YRIB, ICT6)
CALL XGRIB(XRIB, ISTEP(1), XMAX(1), IAXIS(1), 10, 1, 0., 0.)
CALL FRAM
305 JV = 2
JCT = 1
315 JS = JCT - 1
CALL HANED(JS)
CALL OUTR(GST, 0(1,JV), TRAX, YRIB, LEAD)
GO TO (325, 335, 345, 355, 365, 375) , JCT
325 JV = 5
JCT = 2
CALL CNDGT
GO TO 315
335 JV = 6
JCT = 3
CALL CNDOSH
GO TO 315
345 JV = 8
JCT = 4
CALL DASH
GO TO 315
355 JV = 10
JCT = 5
CALL DOT
GO TO 315
365 JV = 13
JCT = 6
CALL DSH('DOT')
GO TO 315
375 CONTINUE
CALL XNDG(1)
CALL PSH(2., 1.5)
CALL TITLE('0, 0, 0, 0, 10, 1, IAXIS(1), YAXIS(1))
CALL FLOG(XRIB, ISTEP(2), YRIB, ICT6)
CALL XGRIB(XRIB, ISTEP(2), XMAX(2), IAXIS(1),
           'OPERATING TIME (DAYS)', 100, 0., 0.)
CALL FRAM
JV = 16
JCT = 7
415 JS = JCT - 1
CALL HANED(JS)
CALL OUTR(GST, 0(1,JV), TRAX, YRIB, LEAD)
JCT6 = JCT - 6
GO TO (425, 435, 445, 455, 465, 505) , JCT6
425 JV = 17
JCT = 8
CALL CNDGT
GO TO 415
435 JV = 19
JCT = 9
CALL CNDOSH
GO TO 415
445 JV = 21
JCT = 10
CALL DASH
GO TO 415
455 JV = 22

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JCT = 11
CALL DOT
GO TO 815
045 JY = 25
JCT = 12
CALL RESET('DOT')
GO TO 815
505 CONTINUE
CALL ENUC(2)
YLEM = INESS('RELATIVE IODINE FLOW RATES', 100)
YORIE = 0. - 0.5 * YLEM
CALL ADLER(90.)
CALL HESSG('RELATIVE IODINE FLOW RATES', 100, - 1.0, YORIE)
CALL BERRY('ANGLE')
CALL ENUF(2)
DO 605 I = 1, LNAX
  DFI00L(I) = Q(X,3) / Q(X,26)
  DFI00P(I) = Q(X,1) / (Q(X,26) * Q(X,27))
  DFI00V(I) = Q(X,2) / Q(X,27)
  DFI11L(I) = R(X,3) / R(X,26)
  DFI11P(I) = R(X,1) / (R(X,26) * R(X,27))
  DFI11V(I) = R(X,2) / R(X,27)
605 CONTINUE
CALL TITLE('TITLE(1,3), - 100, 0, 0,
1 'PLANT DETENTION FACTORS', 100, XAXIS(2), YAXIS(2))
YCYCLE = YAXIS(2) / ALOG10(DPFI00P(1) / DPFI00V(1))
CALL PLOG(XMIN, ISTEP(2), DPFI00(1), YCYCLE)
CALL HOURS(XMIN, ISTEP(2), XMAX(2), XAXIS(2),
1 'OPERATING TIME (DAYS)', 100, 0., 0.)
CALL PRIME
ICT = 0
725 ICT = ICT + 1
IS = ICT - 1
CALL MARKED(IS)
GO TO (735, 765, 795), ICT
735 CALL RESET('DOT')
CALL OUTPDC(ST, DFI00L, DFMAX(1), DFMIN(1), LNAX)
GO TO 725
765 CALL DASH
CALL OUTPDC(ST, DFI00V, DFMAX(1), DFMIN(1), LNAX)
GO TO 725
775 CALL DOT
CALL OUTPDC(ST, DFI00P, DFMAX(1), DFMIN(1), LNAX)
775 ICD = ICT
785 ICT = ICT + 1
IF (ICT .GT. 6) GO TO 935
ICI = ICT - ICD
IS = ICT - 1
CALL MARKED(IS)
GO TO (795, 815, 835), ICT
795 CALL RESET('DOT')
CALL OUTPDC(ST, DFI11L, DFMAX(1), DFMIN(1), LNAX)
GO TO 785
815 CALL DASH
CALL OUTPDC(ST, DFI11V, DFMAX(1), DFMIN(1), LNAX)
GO TO 785
835 CALL DOT
CALL OUTPDC(ST, DFI11P, DFMAX(1), DFMIN(1), LNAX)
935 CONTINUE
CALL RESET('DOT')
CALL ENUF(3)
CALL TITLE('TITLE(1,4), - 100, 0, 0,
1 'RELATIVE RADIOACTIVITIES', 100, XAXIS(2), YAXIS(2))
YCYCLE = YAXIS(2) / ALOG10(ACFMAX / ACTMIN)
CALL PLOG(XMIN, ISTEP(2), ACTMIN, YCYCLE)
CALL ICDAYS(XMIN, ISTEP(2), XMAX(2), XAXIS(2),
1 'OPERATING TIME (DAYS)', 100, 0., 0.)
CALL PRIME
1005 IV = 2
ICT = 1
1015 IS = ICT - 1
CALL MARKED(IS)
CALL OUTPDC(ST, EBRATO(1,IV), ACTMAX, ACTMIN, LNAX)
GO TO (1025, 1035, 1045, 1055, 1065, 1105), ICT
1025 IV = 11
ICT = 2
CALL CHRODT
GO TO 1015
1035 IV = 14
ICT = 3
CALL CHROSH
GO TO 1015
1045 IV = 16
ICT = 4
CALL DASH
GO TO 1015
1055 IV = 17
ICT = 5

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CALL LOT
GO TO 1315
1065 IV = 10
ICT = 6
CALL RESET('DOT')
GO TO 1015
1105 CONTINUE
CALL ZDDP1(0)
CALL TITLE(TITLE(1,5), -100, 0, 0,
1 'PERCENTAGE (CANS OF FEED) %', 100, XAXIS(2), YAXIS(2))
ICYCLE = YAXIS(2) / ALOG10(IODHAI / IODHIA)
CALL YLOG(XHAI, YSTEP(2), IODHAI, ICYCLE)
CALL XGHAIS(XHAI, YSTEP(2), IHAH(2), YAXIS(2),
1 'OPERATING TIME (DAYS) %', 100, 0., 0.)
CALL PBRHE
1205 IV = 2
ICT = 1
1215 IS = ICT - 1
CALL HARKEN(IS)
CALL OUTDIN(ST, YEN(1,IV), IODHAI, IODHIA, LRAH)
GO TO (1225, 1235, 1245, 1255, 1265, 1275, 1285, 1295, 1305,
1 1315, 1325, 1335, 1355) , ICT
1225 IV = 3
ICT = 2
CALL CHDDOT
GO TO 1215
1235 IV = 4
ICT = 3
CALL CHDASH
GO TO 1215
1245 IV = 5
ICT = 4
CALL DASH
GO TO 1215
1255 IV = 7
ICT = 5
CALL DOT
GO TO 1215
1265 IV = 9
ICT = 6
CALL CHDDOT
GO TO 1215
1275 IV = 11
ICT = 7
CALL CHDASH
GO TO 1215
1285 IV = 10
ICT = 8
CALL DASH
GO TO 1215
1295 IV = 15
ICT = 9
CALL DOT
GO TO 1215
1305 IV = 16
ICT = 10
CALL RESET('DOT')
GO TO 1215
1315 IV = 17
ICT = 11
CALL CHDDOT
GO TO 1215
1325 IV = 18
ICT = 12
CALL CHDASH
GO TO 1215
1335 IV = 19
ICT = 13
CALL DASH
GO TO 1215
1355 CONTINUE
CALL RESET('DASH')
CALL ZDDP1(5)
CALL PHYSOR(2., 5.)
CALL TITLE(TITLE(1,6), 100, 0, 0, IN , 1, XAXIS(1), YAXIS(1))
ICYCLE = YAXIS(1) / ALOG10(IODHAI / IODHIA)
CALL YLOG(XHAI, YSTEP(2), 0.1, ICYCLE)
CALL XGHAIS(XHAI, YSTEP(2), IHAH(2), XAXIS(1), IN , 1, 0., 0.)
CALL PBRHE
DO 1695 I = 1,5
GO TO (1665, 1675, 1685, 1695, 1655) , I
1625 CALL CHDDOT
GO TO 1665
1635 CALL CHDASH
GO TO 1665
1645 CALL DASH
GO TO 1665
1655 CALL DOT

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1665 CALL MARKER(I)
      CALL OUTROC(SY, DP(251,2), LOR 05, 0.1, LMAX)
1695 CONTINUE
      CALL RESET('BO')
      CALL ENDGB(1)
      CALL PRYSCR(2., 1.5)
      CALL TITLE(0, 3, 0, 0, 1H, 1, YAXIS(1), YAXIS(1))
      CALL TLOC(DRIB, ISTOP(2), 0.1, FNCLE)
      CALL XCRAYS(TMIN, ESTP(2), XMAX(2), YAXIS(1),
1      'OPERATING TIME (DAYS)S', 100, 0., 0.)
      CALL PRNZE
      DO W95 I = 1,5
        GO TO (1065, 1025, 1035, 1045, 1055) , I
1025 CALL CHROBT
        GO TO 1065
1035 CALL CHROSH
        GO TO 1065
1045 CALL DASH
        GO TO 1065
1055 CALL DOT
1065 CALL MARKER(I)
      CALL OUTROC(SY, DP(1,1), LOR 05, 0.1, LMAX)
1095 CONTINUE
      CALL ENDGB(2)
      YLRC = XMESS('UNIT DECONTAMINATION FACTORS?', 100)
      TORIC = 0. - 0.5 * YLRC
      CALL ANGLE(90.)
      CALL MESSAG('UNIT DECONTAMINATION FACTORS?', 100. - 1.0, TORIC)
      CALL RESET('ANGLE')
      CALL ENDPI(5)
      CALL DOWNFI
      RETURN
9005 FORMAT (010, 0)
9015 FORMAT (10(27, 13))
      END

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