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IODINE-131 RELEASES FROM THE HANFORD SITE, 1944 THROUGH 1947

VOLUME 1 - Text

Hanford Environmental Dose Reconstruction Project

C. M. Heeb

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Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

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This document has been reviewed and approved by the Technical Steering Panel.

J. E. Till, Chair
Technical Steering Panel

March 23 1993
Date

PREFACE

In 1987, the U.S. Department of Energy (DOE) directed the Pacific Northwest Laboratory (PNL), which is operated by Battelle Memorial Institute, to conduct the Hanford Environmental Dose Reconstruction (HEDR) Project. The DOE directive to begin project work followed a recommendation by the Hanford Health Effects Review (HHER) Panel in 1986. The HHER Panel was formed to consider the potential health implications of past Hanford Site releases of radioactive materials. The HEDR Project objective is to estimate radiation doses to individuals and population groups from exposure to radioactive emissions that began in 1944 at the Hanford Site.

An 18-member Technical Steering Panel (TSP) was selected by the Vice Presidents for Research at major universities in Washington and Oregon to direct the project work. The TSP consists of experts in the various technical fields relevant to HEDR Project work and representatives from the states of Washington, Oregon, and Idaho; Native American Tribes; and the public.

A December 1990 Memorandum of Understanding between the Secretaries of the DOE and the U.S. Department of Health and Human Services (DHHS) transferred responsibility for managing the DOE's dose reconstruction and exposure assessment studies to the DHHS. This transfer resulted in the current contract between Battelle Pacific Northwest Laboratories (BNW) and the Centers for Disease Control (CDC), an agency of the DHHS, to continue the project. The TSP continues to act as technical director for the work conducted by Battelle.

The first step in determining radiation doses from Hanford Site operations is to determine the radionuclide content, magnitude, and timing of releases from plant stacks to the air, from reactor coolant discharge lines to the Columbia River, and from liquid waste storage facilities to groundwater. Incidental releases from other facilities will also be determined as part of the HEDR Project Source Term Task.

In Phase I of the HEDR Project, preliminary estimates were made of the iodine-131 sources for the period 1944 through 1947 on a monthly basis (Heeb and Morgan 1991). These estimates formed an initial basis for Phase I dose

estimates (PNL 1991). The HEDR Project plan called for the best estimates that could be made with the reference sources available at the time to form an initial estimate of the iodine-131 doses (Shipler 1991, p. 4.2-4.5).

This report provides the final definition of the iodine-131 source term for the 1944 through 1947 period. This time period was selected because Napier (1992) estimated that over 98% of the historical Hanford radiation dose occurred during early Hanford operations, when the environmental release control technology was new and under development.

Detailed data used in the calculations described in this document are contained in the companion document *Iodine-131 Releases From the Hanford Site 1944 Through 1947, Volume 2 - Data.*

The results reported here form the input to the Regional Atmospheric Transport Code for Hanford Emission Tracking (RATCHET) (Ramsdell and Burk 1992) that will provide the geographical iodine-131 deposition pattern. A series of computer models will turn the geographical deposition of iodine-131 into concentration levels in food and, finally, in dose estimates for affected individuals. The computer models work together and are collectively called the Hanford Environmental Dose Reconstruction Integrated Codes (HEDRIC) (Shipler 1992).

This report completes HEDR Project Milestone 0302A, Documented Phase I Iodine-131 Releases. *It is the final report, replacing the previous version dated October 1992. Appendix C is a record of the TSP comments and BNW responses that have been addressed in this final report. Changes from the October 1992 version are shown in italics.*

ABSTRACT

Releases of fission product iodine-131 are calculated for the 1944 through 1947 period. Releases to the atmosphere were from the ventilation stacks of T and B separation plants. A reconstruction of daily separation plant operations forms the basis of the releases. The reconstruction traces the iodine-131 content of each fuel discharge from the B, D, and F Reactors to the dissolving step in the separation plants.

Statistical computer modeling techniques are used to estimate hourly release histories based on sampling mathematical distribution functions that express the uncertainties in the source data and timing. The reported daily, monthly, and yearly estimates are averages and uncertainty ranges are based on 100 independent Monte Carlo "realizations" of the hourly release histories.

EXECUTIVE SUMMARY

INTRODUCTION

In 1941, President Roosevelt directed the War Department to develop nuclear weapons. The Hanford Site was selected for part of this national effort, known as the Manhattan Project. Construction started at Hanford in 1943. A nuclear reactor, the B Reactor, became operational in September 1944, followed by the D and F Reactors in 1945. The same design was used for all three reactors. Each reactor was fueled with natural uranium, part of which was converted into plutonium by the reactor neutron flux. The irradiated fuel was removed from the reactor and sent to one of two separation plants, T Plant and B Plant. The mixture of uranium, plutonium, and other materials was chemically treated to extract and purify the plutonium. The purified plutonium, formed into metallic disks about the size of hockey pucks, was shipped offsite to be incorporated into nuclear weapons.

During the irradiation of uranium in the reactor, many nuclides other than the plutonium product were created. One of these nuclides was the radioactive isotope of iodine, iodine-131. This nuclide is of greatest concern because it is the largest contributor to the historical Hanford dose. Iodine-131 has a half-life of 8 days, decaying into nonradioactive xenon. During the processing of the fuel from the reactors, iodine-131 gas was released to the atmosphere and dispersed by the wind. The iodine-131 settled on the ground and rivers, and entered the food chain.

As knowledge of the harmful effects of radiation increased, concerns were raised about the impact of Hanford operations on the surrounding population. Furthermore, the continuing declassification of historical Hanford documents made the public more aware of the possibility of health effects to residents of the area surrounding the Hanford Site.

In 1987, the U.S. Department of Energy directed a full study of the release of radi*oactivity* from Hanford and the dose received by the surrounding population. Thousands of additional previously classified documents were

declassified to make them available to the public. This study was directed by an independent Technical Steering Panel (TSP) composed of knowledgeable individuals who were not associated with the U.S. Department of Energy.

SCOPE

11,12 This study analyzes activity at the three production reactors and the two separations facilities that were operating in the 1944-through-1947 period. The three reactors were graphite-moderated, water-cooled reactors located along the Columbia River. The reactors released *virtually no* iodine-131, but it was necessary to study them because they were the source of iodine-131. The time delay between irradiation and processing was also vital, because the amount of iodine-131 decreased by half every 8 days. Irradiated uranium fuel rods discharged from the reactors were dissolved at the chemical processing facilities, T and B Plants, in the first step of plutonium extraction. The iodine-131 was released through the T and B Plant stacks during dissolution and, to a lesser extent, during the subsequent steps in the bismuth phosphate separation process.

9,13 This study focuses on iodine-131 because it *readily enters the food chain and is concentrated in the body by the thyroid gland. Other radionuclides released to the air and to the Columbia River contribute much less radioactive dose to the effective whole body dose (Napier 1992).*

The time period of this study begins with the start of operations in 1944 and concludes at the end of 1947. That cutoff date was chosen because the irradiated fuel was cooled for a longer period before dissolution by the end of the period, allowing natural decay to eliminate much of the radioactive iodine. Later on, filters and chemical scrubbers were installed in the stack air system, which further reduced the iodine-131 emissions.

14,21 This report describes one step in the total process of determining the iodine-131 exposure any particular individual may have received. The total process uses four integrated computer models under the collective name Hanford Environmental Dose Reconstruction Integrated Codes (HEDRIC). The first computer model, Source Term Release Model (STRM), uses plant records and the physical laws governing the nuclear and chemical reactions to arrive at the

amount of iodine-131 released from the plant stacks, as described in this report. Additional computer models are required to determine the dose received by an individual. The second model, *Regional Atmospheric Transport Code for Hanford Emissions Tracking (RATCHET)*, gives the geographical deposition of the iodine-131 after its release. The third *model, Dynamic EStimates of Concentrations and Accumulated Radionuclides in Terrestrial Environments (DESCARTES)*, tracks the iodine-131 through the food products produced in the area under study. The fourth model, *Calculation of Individual Doses from Environmental Radionuclides (CIDER)*, combines the food product information with time, location, and diet data about an individual to estimate that individual's dose *from* iodine-131 from Hanford operations.

TECHNICAL APPROACH

15 Calculating the release of iodine-131 requires the integration of much input and many intermediate calculations. This study relied on original records generated during the time period under study. These were supplemented with other reports and summaries. Wherever possible, multiple sources were used to arrive at values. A knowledge of the physical processes, monitoring techniques used, and completeness of records allowed *the* uncertainty to be *estimated* for each value. This study generated estimates of the iodine-131 releases on an hourly basis. These are the primary inputs to the HEDR Atmospheric Transport Task. In this report, daily, monthly, and yearly summaries are provided.

16 The creation of iodine-131 in the reactors was calculated from reactor power records. The production of this isotope is directly related to the power level, which is recorded in the reactor daily logs. As the amount of iodine-131 in the irradiated reactor uranium fuel increases during reactor operation, it also decreases as a result of decay until it reaches *equilibrium and thereafter remains* a constant amount. If the reactor shuts down, production of iodine-131 ceases and the amount present at shutdown decreases by radioactive decay. The calculations were based upon the daily power records and took into account the day-by-day changes in the amount of iodine-131 present in the fuel.

16 When the irradiated fuel is discharged from the reactor, iodine-131 decays *with an 8-day half life*; the decay time, known as cooling, was inferred from records showing when fuel was discharged from the reactor and when it may have entered the dissolving process.

The next consideration was the process of dissolving the fuel in the separation plants (T and B Plants). This was a two-step process. First, the aluminum cladding was dissolved with a caustic solution of sodium hydroxide, then the fuel was dissolved with nitric acid. The iodine-131 was released during this step and also during processing steps after dissolving. Detailed plant records on the dissolution of batches of fuel were correlated with reactor discharge records to determine the amount of iodine-131 present during dissolving. The fraction of the iodine in the dissolver that was released directly to the stack as well as during subsequent processing was taken into account.

RESULTS

18,19,22 *The estimated* amount of iodine-*131* released to the atmosphere from T and B Plants between 1944 and the end of 1947 was 685,000 curies (Ci). This is summarized by month in Table S.1. *The values provided for each month are the mean (Ci/month), standard deviation (SD), maximum (Max) and minimum (Min) from 100 independent runs of the Source Term Release Model (STRM). The values in Table S.1 for the entire period of 1944-1947 are based on the accumulated releases from the same 100 runs.* Each of these runs represents a possible pattern of hourly releases that could have happened given the uncertainty in the available information.

17 The 685,000 Ci release estimate exceeds the estimate from the Phase I study, which was 406,000 Ci (Heeb and Morgan 1991). The 685,000 Ci estimate is based on plant records that had been retired and warehoused, and were not known to exist during Phase I. The Phase I results were based on monthly average values of the amount of material processed and the cooling time, which came from HWN-1991 (Roberts 1957), the only source of information that covered the 1944 through 1947 period known at the time Phase I results were produced.

TABLE S.1. Monthly Iodine-131 Releases (Ci) From T and B Plants, 1944-1947

Month	1944 Ci/Month	SD	Max	Min	1945 Ci/Month	SD	Max	Min
January					1221	438	2098	131
February					2126	393	2944	1371
March					2082	322	2803	1236
April					28746	1810	33284	25445
May					74482	4747	86615	65245
June					46466	2798	54781	40989
July					47036	2884	53838	41177
August					72090	4940	84752	60761
September					88682	5076	99902	77224
October					92066	5292	106359	83959
November					37752	2441	46652	31856
December	2139	468	3211	1393	62340	3423	71236	55566
TOTALS	2139	468	3211	1393	555089	30056	627939	499183

	1946 Ci/Month	SD	Max	Min	1947 Ci/Month	SD	Max	Min
January	11753	718	13200	10406	6158	395	7248	5443
February	7399	421	8340	6464	3835	277	4541	3219
March	7952	506	9262	6629	5617	332	6359	4951
April	11680	696	13491	9956	4853	380	5814	4127
May	13280	760	15066	11832	3989	286	4672	3384
June	4609	277	5280	4085	1652	126	2019	1359
July	5558	330	6408	4864	2297	136	2632	2031
August	8642	526	9685	7423	1249	93	1421	1067
September	7670	566	8742	6293	1206	77	1407	1044
October	4819	349	5808	4160	472	37	547	365
November	5525	381	6412	4640	261	21	334	222
December	7398	456	8338	6410	261	17	312	221
TOTAL	96284	5139	108929	86752	31848	1714	36295	28951
			Total Released 1944-1947		685359	36895	775092	616400

Note: SD, Max, Min totals are not the result of adding monthly values. They are yearly statistics.

The current results represent a substantial improvement. They are based on a daily reconstruction of plant operations instead of monthly averages and involve overlapping information contained in multiple source documents. Additionally, the calculations model the uncertainties involved in extracting quantitative information from the primary sources.

20 Because of the wealth of original documentation and redundant sources, there is a high degree of confidence that the actual values fall within the computed ranges. If previously undiscovered records should appear, they could

change *the estimated magnitude* of uncertainty for some estimates, but the current base estimates are expected to remain valid. The complete picture given by these records is responsible for both the revised estimate of iodine-131 released and for the high level of confidence in that figure.

RECOMMENDATIONS

All the pertinent records known to exist have been used to arrive at these results. The method of reconstructing the iodine-131 releases uses statistical modeling techniques, which take into account the areas where complete information was not found. It is, therefore, concluded that a sufficiently well-defined estimate of the iodine-131 releases has been obtained, and it is further recommended that these estimates be used as input to the HEDR air transport model as the second step in determining the doses received by the public from Hanford Site iodine-131 releases in the 1944-through-1947 time period.

ACKNOWLEDGMENTS

This report builds on a basis provided by staff members who first attacked the formidable task of estimating iodine-131 emissions from the Hanford Chemical Separations Facilities during a period that began 40 years before the beginning of the Hanford Environmental Dose Reconstruction (HEDR) Project. The staff members who made significant early contributions to this include L. L. Burger, L. G. Morgan, P. O. Jackson, and K. D. Wiemers.

The author would especially like to acknowledge the contribution made by S. P. Gydesen, whose efforts in locating Hanford documents were invaluable in making this reconstruction of the iodine-131 source possible.

J. C. Simpson designed and implemented the Reactor Model. This was a key element in the release estimates because it supplied the power history of each fuel discharge. This information was not recorded in the plant reports and is the most important parameter for calculating the iodine-131 content of discharged fuel. J. C. Simpson also developed the method for allocating dissolver release to hours.

The author would also like to thank the reviewers of the preliminary draft of this document; their comments were invaluable.

GLOSSARY

8	**100 Area**	*Designation for all Hanford Reactor Areas. For example, the fenced exclusion area around B-Reactor was designated 100-B.*
	200 Area	*Designation for all Hanford Separations Areas. For example, Redox is located in the 200W exclusion area.*
	300 Area	*The area nearest Richland which contains the fuel fabrication operations.*
	B Plant	Second bismuth phosphate separation process plant built at the Hanford Site.
	B Reactor	The first Hanford Production Reactor.
	Batch	Amount of fuel dissolved at a time. Synonymous with cut.
	Bucket	The square metal container of discharged fuel elements.
	Burnup	Thermal energy generation. Units are megawatt days (MWd).
	Charge	Amount of fuel loaded into the dissolver. Units are tons.
	Curie	A unit of radioactivity: 3.7×10^{10} disintegrations per second.
	Cut	Amount of fuel in the dissolver that is dissolved at one time.
	D Reactor	The second Hanford Production Reactor.
	Days	Working shift from 8 a.m. to 4 p.m.
	Dissolver	The process vessel used in the spent fuel dissolution process portion of the bismuth phosphate separation process.
	DOI	HEDR computer code used to model separation plant dissolver operations.
	Effective Central Tubes (ECT)	The ratio of the pile power to the average of the 10 highest-powered tubes. In the early period, only the highest-powered tube was used in computing ECT. The radial peaking factor is equal to the number of physical tubes (2004) divided by the ECT.

Exposure	Thermal energy generation per unit fuel mass (MWD/ton).
F Reactor	The third Hanford Production Reactor.
Fission Yield	Fractional amount of a given nuclide per fission event.
Graveyard	Working shift from midnight to 8 a.m.
Half-Life	The time for half of a given mass of a radionuclide to decay.
HEDR	Hanford Environmental Dose Reconstruction (Project).
Heel	Amount of uranium left in dissolver after last cut was processed.
HPR	Hanford Production Reactor.
Lag Time	The number of days between the dissolution and extraction steps in the bismuth phosphate separation process.
Load or Loading	The number of tons of uranium contained in the reactor. Also one of the distribution functions used to model uncertainty in the pile loading.
Monte Carlo	The technique of representing uncertainty in one or more parameters by randomly sampling distribution functions which express parameter uncertainty. The results of each complete sampling (realization) are recorded, for analysis of computed uncertainty of the outcome.
Peaking Factor (PF)	The ratio of the average power generation of a batch of discharged fuel to the average reactor power.
Phase I	Preliminary phase of HEDR Project.
Pile	An earlier term for the graphite-moderated production reactors.
Power	Reactor thermal power. Usual units are megawatts.
Power Peaking Factor	The ratio of the maximum process tube power to the average process tube power.
Process Tube	The aluminum tube which held the uranium fuel elements (slugs) plus cooling water.
Push	Fuel discharge during a given refueling outage. Units are either slugs or tons.

Reactor	Nuclear reactor. Used interchangeably with "pile."
Reactor Model	A computer model developed to provide the relative power experienced by fuel discharged from a Hanford reactor.
Realization	A particular pass through a Monte Carlo simulation where all stochastic parameters have been assigned a value. The simulation represents a "possible reality."
Release Factor	Ratio of radionuclide released to amount of radionuclide processed.
Shift	A portion (usually 8 hours) out of 24 hours for scheduled work. At Hanford these were Days (8 a.m. to 4 p.m.), Swing (4 p.m. to midnight), and Graveyard (midnight to 8 a.m.).
Slug	The aluminum-clad cylindrical uranium fuel element used in Hanford reactors.
Source Term	The amount of radioactivity (curies) of a radionuclide released to the environment from an industrial facility at the point of loss of engineering control.
Stack	The primary release point of exhaust air from a reactor or separation plant building.
STRM	Source Term Release Model. HEDR Monte Carlo computer code which was used to calculate iodine-131 releases.
Swing	Working shift from 4 p.m. to midnight.
T Plant	First bismuth phosphate separation process plant built at the Hanford Site.
Ton	Always 2000 lb in Hanford reactor usage. (Metric tons, 2200 lb, were used only within the separation plants.)

CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

25 The Hanford Site was built to provide plutonium for the United States nuclear weapons program. During the course of operations, some by-product radionuclides, including iodine-131, were released to the air. This section provides background information, outlines the background and reasons for this study, and defines the topics covered.

1.1 BACKGROUND

In 1941, President Roosevelt directed the War Department to develop nuclear weapons. The Hanford Engineer Works was started in 1943 as part of the Manhattan Project. It was intended to produce the element plutonium, one of two known obtainable elements that could be used to produce nuclear weapons. To produce plutonium, it was necessary to irradiate uranium with neutrons. The neutrons would be absorbed by the uranium nucleus, eventually leading to the production of plutonium. In 1943, 1944, and 1945 three nuclear reactors (B, D, and F) were built and operated to provide the neutrons. The reactors were fueled with uranium rods. The production of neutrons by the process of nuclear fission also produces a large number of radionuclides from the fragmentation of the uranium nucleus. One of these is iodine-131.

24 The amount of plutonium in the uranium fuel rods increased as the reactor operated. *When a group of rods reached the goal exposure, the reactor was shut down and the group* of rods *was* discharged. In addition to plutonium, iodine-131 was contained in the rods at discharge. The iodine-131 undergoes radioactive decay at a rate which leaves only half of it after 8 days. The discharged fuel rods were stored for 30 days or longer to allow for the decay of iodine-131 as well as many other fission product radionuclides.

After storage, the fuel rods were sent to the chemical separation facility to extract the plutonium. The first step in the separations process was to load the irradiated fuel rod into a large tank called a dissolver. It was equipped with inlet and outlet pipes as well as a water-cooled reflux condenser on the lid. A so-called dissolver off-gas line, connected near the top of the condenser, led to a large-diameter stack 200 feet high.

After loading, the aluminum cladding of the fuel rods was dissolved with a sodium hydroxide solution. The next step was to dissolve the now-bare uranium fuel rods in concentrated nitric acid. During this process step, part of the iodine-131, along with other volatile radionuclides, was released from the uranium metal and routed through the reflux condenser to the off-gas line and out the stack.

After dissolving, the plutonium was left in the acid solution along with the remaining iodine-131 and other fission product radionuclides. The plutonium was obtained in relatively pure form in the next several processing steps. The remaining iodine-131 and other fission products ended up in the plant high-level waste stream; however, some of the iodine-131 escaped to the separation plant building ventilation air. The ventilation system also exhausted up the 200-foot stack, so some of the iodine-131 was vented to the atmosphere after the dissolving step was completed.

1.2 PURPOSE

The purpose of this report is to document the releases of iodine-131 to the atmosphere from Hanford from 1944 through 1947.

26 The preliminary results of the HEDR Project confirmed that iodine-131 released during the 1944-through-1947 period was responsible for over 98% of the historic Hanford dose (Napier 1992, *p. 9*). A preliminary estimate of early iodine-131 releases on a monthly basis was made during Phase I of the HEDR Project (Heeb and Morgan 1991).

The Phase I results were based on a single reference source (Roberts 1957) with no corroborating references. The data used were averaged on a monthly basis. Hanford documents, which would make a much more detailed reconstruction of the iodine-131 releases possible, were discovered as part of the ongoing HEDR data-gathering activity after the Phase I study ended.

This report describes one step in the total process of determining the iodine-131 exposure any particular individual may have received from operations at Hanford. The following list, along with Figure 1.1, gives a thumbnail sketch of the entire process. The process uses a series of computer

models designed to work together under the collective name Hanford Environmental Dose Reconstruction Integrated Codes (HEDRIC).

27 • The laws of physics and chemistry describe the reactions that took place in the nuclear reactors and chemical processing plants. The records that were kept at the plants describe the materials that went into the process. Data from those records are entered into a mathematical model of the operation of the processes. That model, the Source Term Release Model (STRM), using the laws of science and the data on Hanford operations, produces an estimate of the amount of iodine-131 that was vented to the atmosphere through the plant stacks. *The* hourly releases of iodine-131 *are* the final product of this report.

• The second model combines the hourly release data with information on wind direction and speed. This model, the Regional Atmospheric Transport Code for Hanford Emission Tracking (RATCHET), yields an estimate of the distance and direction the iodine-131 went before settling on the ground and on crops.

• The third model, Dynamic EStimates of Concentrations and Radionuclides in Terrestrial EnvironmentS (DESCARTES), takes the distribution of iodine-131 and calculates its progress through the food chain. Ultimately, DESCARTES describes the iodine-131 concentration in the foods available to the population in the area covered by the HEDR Project.

• The final model, Calculation of Individual Doses from Environmental Radionuclides (CIDER), uses time, location, and diet information for an individual and the DESCARTES information on iodine-131 in the food to calculate the dose estimate—how much iodine-131 from Hanford operations ended up in that individual's body.

The release information in this report is now based on multiple reference sources and reconstructs the release of iodine-131 on an hourly basis based on plant operations. Each reactor discharge and each dissolver batch of reactor fuel dissolved is represented. This forms a recreated base of original operational information which can form the basis for independent estimates of atmospheric dispersion, deposition, and dose estimation for radionuclides other than iodine-131.

1.3 SCOPE

The Hanford facilities that produced and released iodine-131 are described. The production of other radionuclides is discussed. The time period of the study is also discussed.

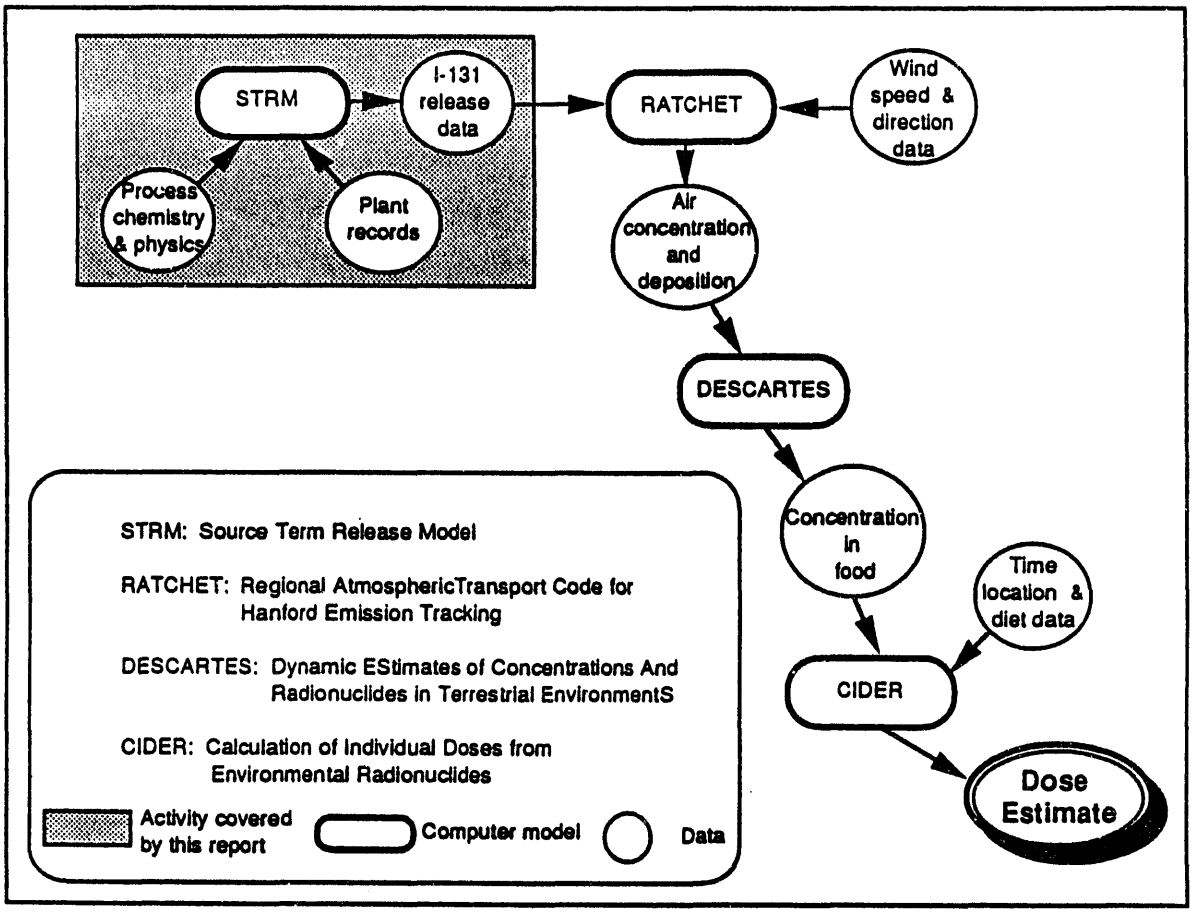

FIGURE 1.1. Hanford Environmental Dose Reconstruction Integrated Codes

1.3.1 Facility Descriptions

28,29 Iodine-131 was created by the nuclear fissioning of uranium fuel in the three Hanford Production Reactors (HPRs). B Reactor started up in September 1944. D Reactor started up in December 1944, followed in February 1945 by the startup of F Reactor. The HPRs, described in Ballinger and Hall (1991), are large graphite cubes *each* with 2004 horizontal aluminum process tubes containing 8-inch aluminum-clad uranium metal cylinders (slugs). *Neutrons were* produced by a neutron chain reaction in the uranium.[a] The neutrons were absorbed by the uranium nucleus, which broke apart (fissioned) producing a

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(a) The use of "uranium" refers to U-235 fusion as well as Pu-239 fusion. The Pu-239 is created by neutron capture by the U-238 nucleus.

large amount of thermal energy and many nuclear fragments (fission products) plus approximately 2.5 neutrons per fission, which was enough to sustain the chain reaction. Iodine-131 is one of many highly radioactive nuclides produced during fission. The graphite served as a "moderator" to slow the high-energy neutrons down, which made them more reactive and better able to sustain the chain reaction.

30 The slugs were clad in aluminum to prevent the uranium from reacting chemically with the cooling water. Because of the heat produced, a large amount of water was required to cool the reactor. The cooling water flowed *horizontally* through the aluminum process tubes from the vertical "front face" to the vertical "rear face" of the reactor. Each process tube was equipped with an outlet water temperature monitor and a flow-measuring orifice or venturi assembly. As thermal power was generated in the slugs from the action of the neutrons, the coolant water was heated. The instrumentation provided a means of calculating individual tube powers (product of tube flow and temperature rise):

$$\text{Power(kw)} = 0.2635 \times \text{Flow(gpm)} \times [T_{outlet}(°C) - T_{inlet}(°C)] \qquad (1.1)$$

The time-integrated power gave the individual tube burnup:

$$\int P(t)dt = E(t) \qquad (1.2)$$

expressed in megawatt-day per ton (MWd/ton). When a group of tubes reached approximately 200 MWD/ton (Jaech undated), the reactor was shut down and the tubes discharged.

30 The irradiated slugs were intensely radioactive, and removing them from the reactor, which was equipped with radiation shielding, required that they be shielded at all times. The discharge operation consisted of opening up the process tube front and rear fittings. New unirradiated slugs were inserted into the front of the tube, which *pushed* the irradiated slugs out the rear of the process tube. The irradiated slugs fell into the water of the discharge chute where they slid under the rear face shield wall into the discharge basin. The water in the discharge and contiguous storage basin was deep

enough to provide shielding for the workers who, using long-handled tongs, picked up the slugs and put them into storage buckets on the floor of the basin. The buckets, which held 105 slugs each, were then moved to a temporary storage location in the storage pool.

After discharge, the slugs were stored at the reactor storage pool, then sent either to the 200 North Area intermediate storage facility (three pools) or directly to T or B Plant. In this early period, all of the fuel was sent to the 200 North Area of the Hanford Site and then dispatched to T and B Plants.

A description of T and B Plants, which used the bismuth phosphate separation process, is given in Ballinger and Hall (1991). T Plant started processing radioactive fuel from B Reactor in December 1944. B Plant began operations in April 1945. In these operations, spent fuel was received via the rail loading bay in the 221B and 221T Buildings. A railroad car with water-filled shielding compartments (well car) contained the spent fuel buckets, each bucket loaded with a nominal 105 slugs.

The separation process started when the slugs from the buckets were put in the dissolver by a remotely operated crane. A nominal dissolver "charge" during this period was 8 buckets, 840 slugs or 3.3 tons (at 7.85 lb per slug). The normal charge was placed in the dissolver on top of an approximately 1.1-ton "heel" of undissolved metal left over from the previous run. The heel was left for speed dissolving of the next fresh charge. Slugs in the heel had a greater surface area than new slugs as a result of being attacked by the nitric acid. Since the acid dissolution rate is roughly proportional to the specific uranium surface area (cm^2/gU), the presence of the heel reduced the dissolution time.

31 The dissolver was fitted with a reflux condenser, which prevented the escape of boiling water vapor. At the top of this condenser was a 3-inch-diameter off-gas line, which was connected to the output side of the *building* vent fan. Volatile materials from the dissolving process were drawn out of the dissolver via a steam jet pump. Dissolver operations were conducted at all times with a negative pressure relative to atmosphere to avoid direct leakage of radioactive gases from shielded pits called processing "cells" into

the building ventilation system. Air pressure of the entire process building was maintained negative relative to atmosphere by the ventilation tunnel exhaust fans (as shown in Figure 1.2). A fraction of the iodine-131 remaining in the process liquid after dissolving was emitted during subsequent processing steps via the canyon ventilation tunnel.

The aluminum cladding was removed from the irradiated slugs loaded into the dissolver by the addition of caustic, concentrated sodium hydroxide. After removing the caustic solution from the dissolver, concentrated nitric acid was added, which was sufficient to dissolve 1.1 tons of the bare uranium slugs. Afterward, two more 1.1-ton "cuts" were made, for a total of three cuts per dissolver charge. Evolution of iodine-131 and other volatile fission products to the dissolver off-gas occurred with each of these cuts. This left an approximately 1.1-ton heel in the dissolver, which was then prepared to receive the next 3.3-ton charge.

1.3.2 Radionuclides

Many radionuclides were produced in the HPRs. About 30 of these (Napier 1992) are considered to be potentially significant contributors to the Hanford dose either by air or by water pathways. Iodine-131 released to the air by T and B Plants in the 1944-through-1947 period was estimated to be the largest of these by a large margin (Napier 1992). The other radionuclides are being studied and doses will be calculated for them as the HEDR Project continues. The beginning of a dose estimate for any of these radionuclides must start with a "source term": an estimate of the amount of curies released and the time of their release. The source terms for other radionuclides are currently being developed, both for air and water releases (Shipler 1992).

1.3.3 Time Period

Effort was concentrated in obtaining the best possible source-term definition for iodine-131 released to the air in the 1944-through-1947 period because it was known to be large (Anderson 1974), and because the records on which to base a source-term reconstruction were the oldest and most vulnerable to deterioration and destruction through the normal functioning of the Federal

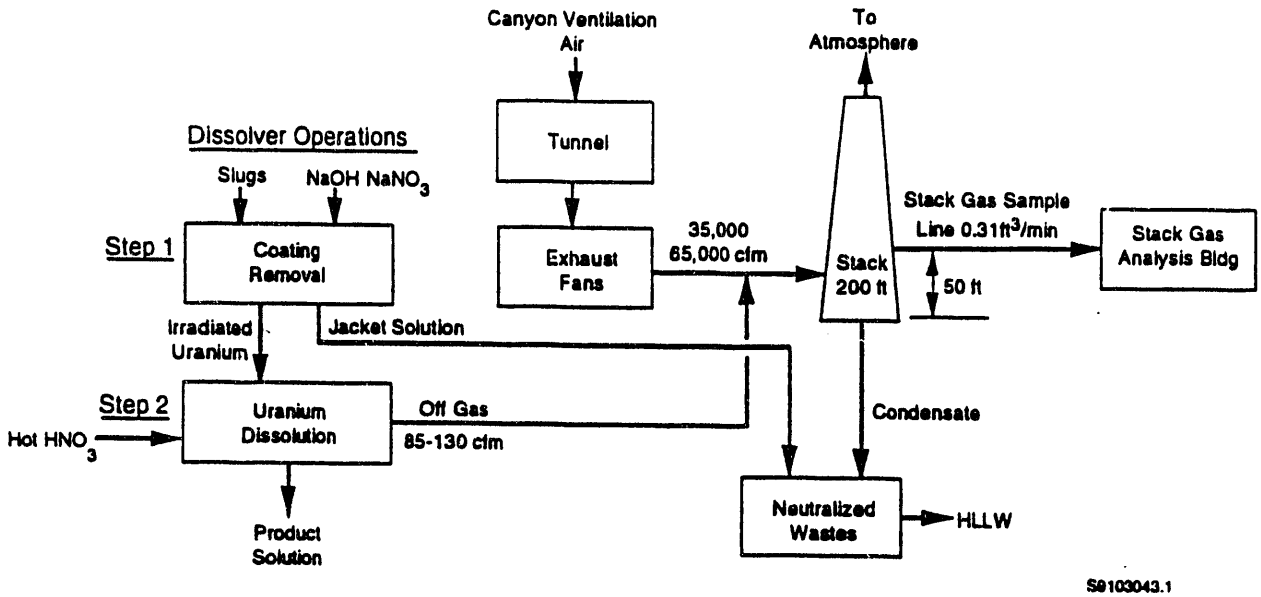


FIGURE 1.2. B and T Plant Stack Air System

Records storage system. Releases to the air during this period were high because cooling times were short and release control technology had just begun and was under development.

1.3.4 Points of Release

The B and T Plant stacks were anticipated to be the largest air-release sources of all the Hanford production facilities (Napier 1992). Their design provided release monitoring systems because they were recognized as air-release points. Other air-release points, such as the reactor ventilation stacks, were minor as far as fission product releases were concerned because fission products created at the reactors were almost entirely contained within the aluminum-clad slugs.

Operations at the 300 Area fuel fabrication facilities during this early period involved only unirradiated uranium. Hence, air releases from these facilities would be minor compared to the separations plant stacks.

1.4 PREVIEW OF THE REPORT

The Technical Approach section of this report (2.0) defines the information required to estimate iodine-131 releases and reviews the existing information base. Section 2.0 then explains how gaps in the required information

were overcome by statistical uncertainty modeling techniques, and the assumptions involved. An overview of the various stages in the computation process is provided.

Section 3.0, Quality Assurance and the Achievement of Data Quality Objectives, discusses the quality objectives of this report and assesses their achievement.

In Section 4.0, Results, the estimates are discussed and compared with Phase I results. The reasons for the larger estimates of the current study compared to Phase I are given. The detailed numerical results, which are tabulated in Volume 2, are described.

Section 5.0 presents the conclusions drawn from this effort including comparisons with the results of previous studies. Finally, Section 6.0 recommends the future use of the results.

Appendix A describes the mathematical model of a Hanford Production Reactor that was used in calculating the production of iodine-131. Appendix B gives an evaluation of the reference documents used to determine the release factor, the percentage of iodine-131 produced that is released to the atmosphere.

2.0 TECHNICAL APPROACH

This section explains how the iodine-131 release estimates were made.

2.1 REQUIRED INFORMATION FOR CALCULATING IODINE-131 RELEASES

The objective is to estimate hourly releases of iodine-131 from T and B Plant stacks in the 1944-through-1947 time period. Hourly release data was selected as the objective to allow correlation with existing hourly wind speed and direction data. What information would be required to calculate hourly releases? First, the amount of iodine-131 present in the fuel discharges, or "pushes," as they were called in the terminology of the day, must be known. Second, because iodine-131 decays with a half-life of 8 days, the number of days between the push and dissolving "cut" (cooling time) must be known to calculate the iodine-131 available for release. Third, the fraction of dissolver iodine released to the stack by the dissolver off-gas line must be known. Fourth, the fraction leaked to the building ventilation from processing steps after dissolving must be known. Fifth, because some fraction of the iodine sent to the stack did not go out the top, but was returned as condensate in the collection trap at the bottom of the stack, this fraction must be known. Sixth, time of day that dissolving started and ended must be known. And, last of all, the hourly release rate that applied while the cut was being dissolved must be known. These requirements are summarized in the following list:

1. Push iodine-131 content
2. Cooling time: difference between when the reactor shut down for the push and when the dissolver cut was made
3. Off-gas line release fraction
4. Post-dissolving release fraction
5. Stack condensate fraction
6. Dissolver cut start and stop times
7. Hourly release profile during cut iodine evolution.

This information was not found in all the detail required in the Hanford historical document records. However, enough was found so that specific data could be used when available, and uncertainty modeling could be used to fill in missing information. Uncertainty modeling requires that enough information be found to construct appropriate distribution functions. The reactor and separation plant records must, therefore, not only supply primary data, but must also supply enough information to construct the uncertainty distribution functions.

2.2 INFORMATION BASE

32 The information base that provided the *data* on the reactor operations and the chemical separation plants are discussed in the following paragraph.

2.2.1 Reactor Information Sources

The P-Department Reports (General Electric Company 1947) are reactor daily reports. They give power level information (megawatts), daily production (megawatt days), number of slugs pushed, and other useful information regarding the distribution of power in the reactor each day for the entire period. This information is used to estimate the reactor iodine-131 content on a daily basis for the entire period. It also provides information to the Reactor Model, which will be discussed in a following section and in Appendix A.

2.2.2 B and T Plant Information Sources

33 The 200 Area Reports (Acken and Bird 1945; Bird and Donihee 1945) contain daily B and T Plant data from 1944 through May 22, 1946, in spite of the 1945 issue date noted in the references. (These were living documents and the 1945 date is the original Hanford Engineer Works Classified Files issue date. Bird and Donihee was issued in 1945, but received plant data as it accumulated through May 1946.) These reports contain an identification of dissolver cuts, and which process step they were in, as of 8 a.m. A sample page is shown in Figure 2.1. The dissolver batch number is in the following

DAILY RUN STATUS AS OF 8 A.M. CANYON-CONCENTRATION BLDGS, (221B-224B) RDO-8 6-6-45

Date			5-31	6-1	6-2	6-3	6-4	6-5	6-6
Section		Process							
221 BUILDING	4	Dissolving	$B_d23,24$	B_d24	MT	D_d1	D_d1	$D_d2,3$	$D_d2,3$
		Storage	$\frac{1}{2}(B_d20,21)22$	$B_d22,23$	$B_d22,23,24$	$\frac{1}{2}(B_d23,24)$	MT	D_d1	D_d1
	8	Extraction	B17	06-B1	MT	B2	B3	MT	MT
	9	Waste	MT	MT	MT	MT	B2	B3	MT
	12	Oxidation	MT	MT	MT	MT	MT	MT	MT
	13	1st By-Prod	MT	B17	B1	MT	B2	B3	MT
	14	1st Prod	MT	B17	B1	MT	MT	MT	B3
	15	Waste	MT	MT	B17	B17,B1	B1	B2	B2,B3
	16	2nd By-Prod	MT	MT	B17	B1	MT	B2	MT
	17	2nd Prod	MT	MT	MT	B17	B1	MT	B2
224 BLDG.	0	Oxidation	MT	MT	MT	MT	MT	MT	MT
	A	Cross over By-Prod	MT	MT	MT	MT	MT	B1	MT
	D	LaF By-Prod	MT	MT	MT	MT	B17	B1	B1
	E	LaF Prod	MT	MT	MT	MT	MT	B17	B17
	F	Metathesis	MT	MT	MT	MT	MT	MT	B17
	G	Waste	MT	MT	MT	MT	B17	MT	MT

FIGURE 2.1. Daily Run Status as of 8 a.m.

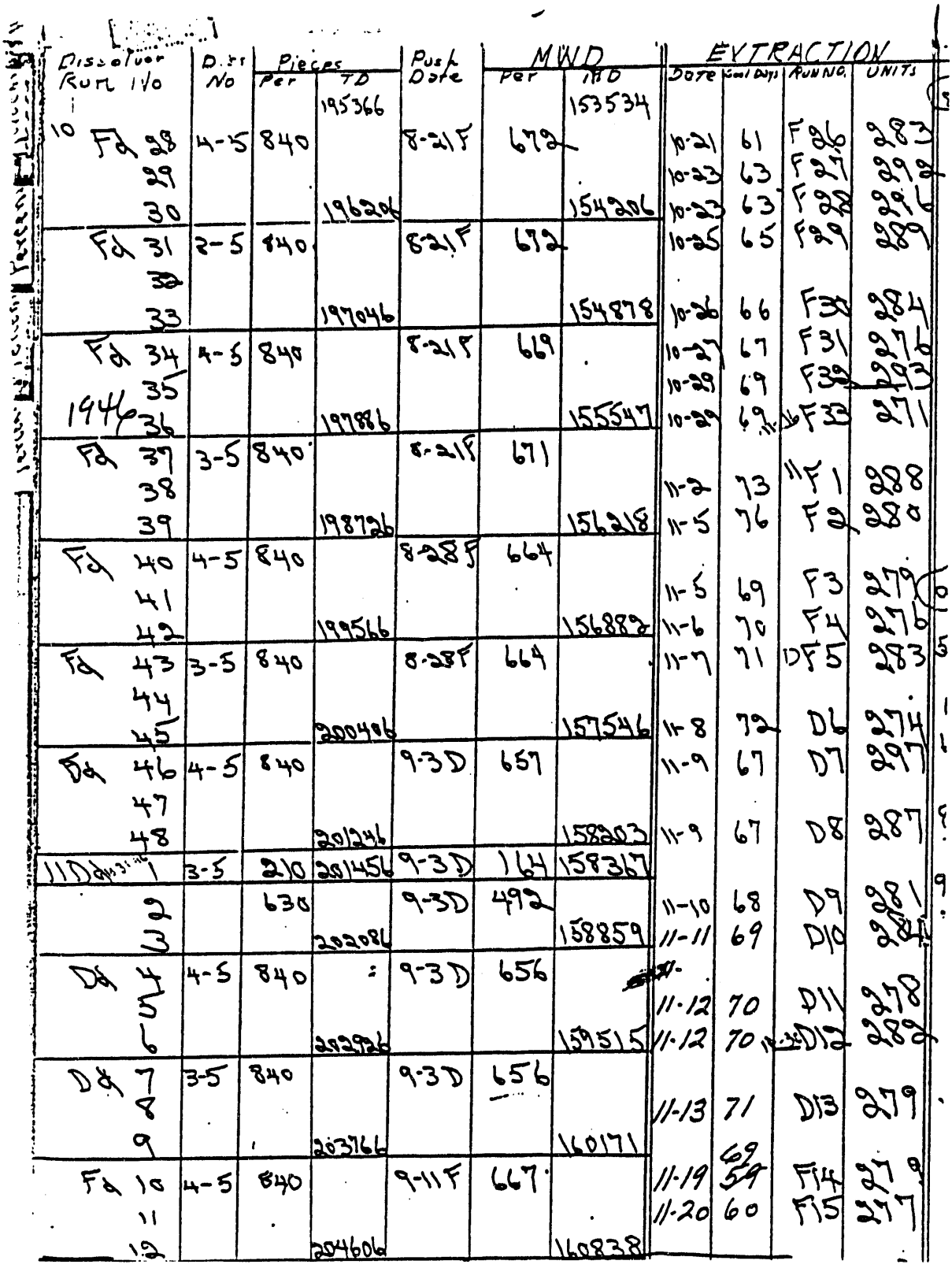
format: Bd24. This means that the cut was from a B reactor push, the "d" meant that it was a dissolver batch number (after dissolution, stored material in solution was redesignated with an extraction batch number), and the "24" meant that it was the 24th cut of the month. The cuts are shown as "in the dissolver" or "in storage."

Unfortunately, no information is given as to exactly what push (date) from the indicated reactor is in the dissolver. This is the primary reference used to reconstruct B and T Plant operations until May 22, 1946.

The Jaech reference (undated) is a computer printout which contains, for both plants, a monthly summary of reactor pushes dissolved, the burnup of the dissolved push (MWd), and the exposure of the fuel (MWd/ton). It also has a handwritten notation giving the cut number of the last cut of the month. A calculated estimate of the number of tons dissolved in each push can be made by dividing the burnup (MWd) by the exposure (MWd/ton). It was used to determine what part of each reactor push was dissolved at T Plant, and what part was dissolved at B Plant. It also helped in the reconstruction of dissolver operation covered by the 200 Area Reports (Lindvig 1945, 1946), since these do not explicitly identify which push is being dissolved.

The Metal History Reports (General Electric Company 1946) information consists of plutonium accountability handwritten ledgers covering the period August 28, 1946, to December 31, 1947. A sample page is shown in Figure 2.2. The dissolver batch number (called "run number" in this reference), the number of slugs, and the push *date* for each dissolver charge are given, as well as the date of extraction. This is nearly a complete information set, except that the date of extraction is given instead of the date of dissolution. The cooling time is the difference between cut dissolution and the reactor shutdown date for the push. The column labeled "TD" is the number of slugs dissolved by the plant since startup.

34 These three references form the basis for reconstructing the "logistics" of T and B Plant operation: tons dissolved and cooling time. There is a blank period from mid-May 1946, when the 200 Area Reports (*Bird 1945*) stop and mid-August 1946, when the Metal History Reports (General Electric



Dissolver Run No.		Die No.	Pieces Per	Pieces TD	Push Date	MWD Per	MWD TD	EXTRACTION Date	Cool Days	Run No.	Units
				195366			153534				
10 Fd	28	4-5	840		8-21F	672		10-21	61	F26	283
	29							10-23	63	F27	291
	30			196204			154206	10-23	63	F28	292
Fd	31	2-5	840		8-21F	672		10-25	65	F29	289
	32										
	33			197046			154878	10-26	66	F30	284
Fd	34	4-5	840		8-21F	669		10-27	67	F31	276
	35							10-29	69	F32	293
1946	36			197886			155547	10-29	69	F33	271
Fd	37	3-5	840		8-21F	671					
	38							11-2	73	11F1	288
	39			198726			156218	11-5	76	F2	280
Fd	40	4-5	840		8-28F	664					
	41							11-5	69	F3	279
	42			199566			156882	11-6	70	F4	276
Fd	43	3-5	840		8-28F	664		11-7	71	DF5	283
	44										
	45			200496			157546	11-8	72	D6	274
Dd	46	4-5	840		9-3D	657		11-9	67	D7	297
	47										
	48			201246			158203	11-9	67	D8	287
11D	1	3-5	210	201456	9-3D	164	158367				
	2		630		9-3D	492		11-10	68	D9	281
	3			202086			158859	11-11	69	D10	288
Dd	4	4-5	840		9-3D	656					
	5							11-12	70	D11	278
	6			202926			159515	11-12	70	D12	289
Dd	7	3-5	840		9-3D	656					
	8							11-13	71	D13	279
	9			203766			160171		69		
Fd	10	4-5	840		9-11F	667		11-19	59	F14	279
	11							11-20	60	F15	277
	12			204606			160838				

FIGURE 2.2. Metal History B Area

Company 1946) begin. Jaech (undated) provides information on the monthly pushes dissolved as well as the number of cuts because of the hand-entered notation of the final cut dissolved each month (i.e., an entry of Dd43 would mean that 43 cuts were dissolved during the month).

The next major information source required is release fraction information. Here, many references were involved. A final selection of the value and distribution of the various release fractions is provided in the following section, and each of the references is described in detail.

The information for developing profiles of hourly releases came from a single source, Health Instruments Department Logbook HEW-823-L (Lindvig 1946). The Health Instruments Department was charged with monitoring plant radiation, and this reference is essentially many logged radiation surveys taken at various sites on the project. Some of the surveys include stack gas sampling measurements of the amount of iodine-131 at approximately 15-minute intervals taken during cut dissolvings. This same reference also provides time-of-day information for more than 300 dissolver cuts.

2.3 UNCERTAINTY MODELING

36 The uncertainties in the data are modeled using Monte Carlo techniques. Basically, this involves characterizing parameter uncertainty by specifying a distribution function for each uncertain parameter. Then a computer run is made wherein a value of each uncertain parameter is supplied by randomly sampling the distribution function. The output values are recorded. Several runs are made using different samplings of the distribution functions. The set of runs then defines the range of possible output values that could result from input parameter uncertainty.

In this case, we are interested in hourly iodine-131 releases. To model the data uncertainties, two Monte Carlo models were written.

35,37 The first of these is the Reactor Model (RM). It is required because of a lack of information concerning the power history of each push. The P-Department Reports (General Electric Company 1947) provide enough information to calculate the *total* pile iodine content, but the iodine content of the

push depends on the location of the discharged process tubes within the reactor. The tube powers varied from about 160% of the average tube power (pile power divided by the number of tubes) located in the central zones to about 40% in the tubes located at the fringe of the reactor. The RM provides this needed information. *Appendix A provides detailed information on the reactor model.*

The second model is the Source Term Release Model (STRM). This model actually produces the hourly iodine-131 releases. It samples all key uncertain parameters during each Monte Carlo run. Results from each run (realization) are written to various files. At the conclusion of a set of runs (100 realizations is the usual amount), it writes iodine-131 averages and standard deviations in several edit formats: cut-by-cut, daily, monthly, and yearly. It also produces a "Met. File," which contains hourly releases for each realization that is used by RATCHET, the atmospheric wind transport computer model (Ramsdell and Burk 1992).

2.4 OVERVIEW OF THE CALCULATIONS

A third computer code that models the dissolver operation was written to provide input to STRM. It is strictly deterministic and produces nominal values of dissolver charges, cuts, and heels from input reactor pushes and dissolving times. It is called DOI. The inter-relationship of the two Monte Carlo codes and DOI is shown in Figure 2.3, along with the attendant input and output files.

The calculation starts with the RM. It has only one input file, which contains the daily power from each of the three reactors from the P-Department Reports (General Electric Company 1947) as well as the burnup of every one of the 226 pushes that were dissolved. Ancillary information on this file is used to provide within-reactor power distribution information to RM. The REACTORS file provides all the reactor information to DOI. The PF file gives results from the Monte Carlo run to STRM.

DOI combines the reactor information with new input for the separation plants via the SPLANTS file. It produces two input files to the STRM model.

Iodine - 131 Calculation Schematic

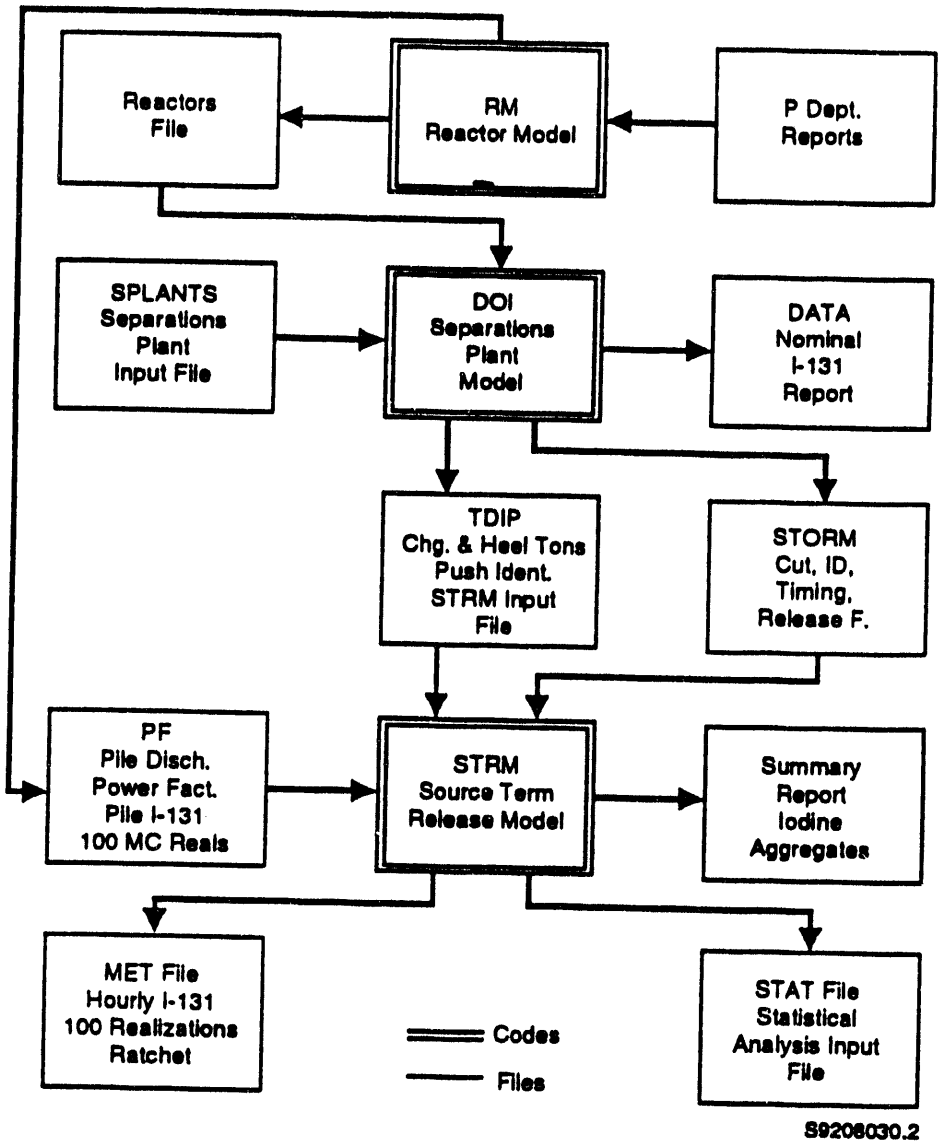


FIGURE 2.3. Iodine-131 Calculation Schematic

The TDIP file contains dissolver cut information. The STORM file conveys release fractions and release timing information to STRM.

STRM calculates the hourly release rates using the three input files: PF (from RM), TDIP (from DOI), and STORM (from DOI). It writes a printed summary report file, the MET file, with hourly releases from the Monte Carlo realizations, and STAT file, which is a record of the sampling results from all distribution samplings from all Monte Carlo realizations.

3.0 QUALITY ASSURANCE AND THE ACHIEVEMENT OF DATA QUALITY OBJECTIVES

In this section, the quality objectives for this work are described with an evaluation of how well those objectives were met. Additionally, the quality assurance procedures implemented are discussed.

3.1 DATA QUALITY OBJECTIVES

This is a retrospective study and the usual procedure of establishing objective criteria for acceptable data quality standards in advance of data acquisition could not apply. Instead, objectives of accuracy, precision, completeness, representativeness, and comparability of potentially available data were set (Shipler 1991a). These objectives were met.

38,39 The data quality objective for accuracy specifies that the calculated monthly release estimates should be within 25% of the actual releases. The actual releases are not known; however, over 100 Monte Carlo realizations were run incorporating the uncertainties of known parameter values. The one standard deviation range was within 10% of the mean value. This assures us that the computed values encompass the actual values with a high *probability*. Comparisons with Anderson (1972) were made in detail and are reported in Section 5.0.

The precision objective to provide a range between minimum and maximum values was met by showing the ranges of estimates and the standard deviation where appropriate. All estimates were subject to full peer review.

The completeness objective was to cover each day and each operating separation plant for the period of the report. This objective was met in the sense that enough original data sources were found to permit the estimation of iodine-131 for every dissolver cut. Any newly discovered source could change the uncertainty bounds on iodine-131 release estimates, but would be unlikely to change the nominal values.

The representativeness objective requires the data to represent all known activities. The P-Department Reports (General Electric 1947), the 200 Area Reports (Lindvig 1945, 1946), and the Metal History Reports (General

Electric Company 1946) are corroborated by the monthly summary data contained in Jaech (undated). The P-Department Reports, the 200 Area Reports, and the Metal History Reports, which formed the basis of dissolver operations reconstruction, are production records and were concerned with plutonium accountability. As such, they probably were independently verified, although no record of this was found. There are many instances where one day's entries are corrected on the following day, which indicates a review was routinely conducted. The Jaech reference was also concerned with plutonium production, but was not a primary production record. It did contain some errors in the exposure of several pushes that were known from the P-Department Reports to be substantially above the nominal goal exposure of 200 MWd/ton. In any case, the discrepancies are documented in Section 4.2.1. In all cases the P-Department Reports were used to determine the discharge fuel amounts because they were primary production records. The peer review confirmed that the representativeness objective had been met.

The comparability objective required the monthly summaries of release estimates to be compared to those of Anderson (1972). Those comparisons are detailed in Section 5.0 and were verified by *a BNW* peer review.

3.2 QUALITY ASSURANCE METHODS

In accordance with the task plan, all data sources were verified and all calculations are traceable from the initial source to the result. Hand calculations were performed according to Battelle procedure PAP-70-301; software procedures SCP-70-312 through 318 were followed where appropriate. These assurance measures were verified by project office quality assurance staff. The following paragraphs provide some specific examples.

The iodine-131 content of each push (as calculated by RM) was verified by an independently written code. Similarly, the iodine-131 content of each cut from STRM run in the deterministic mode (no Monte Carlo sampling) was verified against values calculated by DOI.

Each sampling result from each distribution function was recorded from 100 realizations and analyzed to check that the results did indeed follow the intended input distribution. This was done for both Monte Carlo codes RM and STRM.

Data entry from records was verified by an independent technical review.

40 *Peer review was accomplished within BNW by HEDR Project Office staff, three BNW senior scientists, and several HEDR staff scientists. All internal comments were resolved, and the documented resolutions are now part of HEDR project records. The TSP review and comment resolutions are documented in Appendix C.*

4.0 RESULTS

The details of the reconstruction of reactor and separations plant operations leading to the release of iodine-131 are given in this section.

4.1 CREATION OF IODINE-131 BY REACTOR OPERATIONS

Iodine-131 content in the pile uranium is determined by solving the following differential equation:

41

$$\frac{dN}{dt} = Y\Sigma_f\phi - \sigma_a\phi N - \lambda N \qquad (4.1)$$

where N = the iodine-131 concentration in nuclei per cm^3

Y = the fractional fission yield of iodine-131

Σ_f = the macroscopic fission cross-section in cm^{-1}

ϕ = the neutron flux in neutrons per cm^2 per second

Σ_a = the macroscopic iodine-131 absorption cross-section in cm^{-1}

λ = the radioactive decay constant of iodine-131 in sec^{-1}

t = time in seconds.

The first term on the right is the production rate from the fission process, and the remaining terms are removal terms due to neutron capture and decay, respectively.

41 The solution of this equation was simplified by neglecting the removal term, $\Sigma_a\phi$, because it is much smaller than the decay term. This can be shown by considering appropriate values of the parameters in the removal term. The microscopic cross-section (σ_a) value for iodine-131 listed in the ORIGEN2 code (Croff 1980) cross-section library for iodine-131 is 0.3229 10^{-24} cm^2. The value λ is ln2/(8.04 days x 86400 sec/day) = 9.98 x 10^{-7} sec^{-1}. The Hanford reactor neutron flux was approximately 10^{+14}. Since $\Sigma_a = N \times \sigma_a$, the removal term on the *right* side of Equation (4.1) can be rewritten as:

41

$$\sigma_a \phi N + \lambda N = N(\sigma_a \phi + \lambda) = N(0.3229 \times 10^{-24} \times 1.0 \times 10^{+14}$$

$$+ 9.98 \times 10^{-7}) \approx \lambda N$$

Also, the flux and the macroscopic fission cross-section can be removed by expressing them in terms of the reactor power level P:

$$P = \kappa \Sigma_f \phi$$

where κ is the thermal energy per fission.

With these approximations and substitutions, the solution to Equation (4.1) is:

$$N(t) = \frac{YP}{\kappa\lambda} (1 - e^{-\lambda t})$$

43 Using 3.7×10^{10} *dis. sec*$^{-1}$ *Ci*$^{-1}$, *201.72* MeV per fission *(Croff 1980)*, an iodine-131 fission yield of 0.0289 (Croff 1980), *1.60176* $\times 10^{-19}$ watt sec/MeV, and moving the decay constant to the left-hand side of the equation gives the final expression for the number of curies of iodine-131 in the pile, which has operated at P megawatts for t days and then decayed (operation at zero power) for T days:

45,53

$$Ci = 24174\ P\ (1 - e^{-0.0862t})\ e^{-0.0862T} \qquad (4.2)$$

In practice, the reactor power varied from the designed power level of 250 MW to zero at shutdown. Several weeks at constant power level would be required for the iodine-131 to reach a steady state (saturation) where the formation rate was equal to the decay rate.

After 53 days of operation, the iodine-131 content would be within 1% of the 24200 P saturation value. To account for the daily fluctuations in pile

iodine-131 content, daily reactor power levels from General Electric Company (1947) supply values for P_i in the following equation:

45,53,69

$$Ci = 24174\ (1 - e^{-0.0862}) \sum_{i=1}^{i=N} P_i\ e^{-0.0862(i-1)} \qquad (4.3)$$

where the index i runs backwards in time, i.e., i=1 on the day of the calculation and i=N for the Nth day before i=1. This accounts for all of the buildup and decay of iodine-131 from the daily power operating history (P_i) for N days prior to the day of the calculation.

47 Equation (4.3) gives the iodine-131 content of the entire pile. This must be related to the iodine-131 content of the fuel in each discharge. To do this, a knowledge of the average specific power (MW/ton) generated by the discharged fuel is required. This, expressed as a ratio of push power to average pile power, is called the peaking factor of the discharge (PF). This is a constant multiplier on each P_i of Equation (*4.3*), which converts the pile power to the power of the push. Thus, the iodine-131 content of each push Ci_d is given by:

45,53

$$Ci_d = 24174\ PF(1 - e^{-0.0862}) \sum_{i=1}^{i=N} P_i e^{-0.0862(i-1)} \qquad (4.4)$$

48 The calculation of the peaking factor is explained in detail in Appendix A *in terms of a simplified 25-ring model. For the 244-ring model used in the calculation, the peaking factor* ranged from 0.4 to 2.0, depending on when a particular discharge occurred. Since the discharge burnup goal was fixed at 200 MWd/ton, the highest-powered tubes were the first to reach this goal and the first discharged. Higher-powered tubes were discharged more frequently than lower-powered tubes from the fringe zone of the pile. The long-term average value approaches 1.10, but this does not occur within the 3 years of the early period, which necessitates the approach taken in Appendix A. During 1945 when cooling times were short (i.e., down to 30 days in a few instances),

the fuel being discharged was from newly started-up reactors. Most of it was coming from the higher-powered (more iodine-131-rich) regions of the three piles because these regions would be the first to reach the 200 MWd/ton goal exposure.

The Reactor Model uses four distributions to describe the uncertainty of its two principal output variables: peaking factor (PF), and daily iodine-131 content (ICON). Distributions were used for the following input variables:

- daily pile power (DPP)
- daily ratio of pile power to maximum tube power (ECT)
- the number of tons of uranium in the pile (LOAD)
- the number of tons discharged (PUSH).

49 A given discharge normally comprised material from more than one modeled reactor region. The PF was calculated for each discharge by mass weighting the ratio of the power in the modeled reactor region of origin to the pile power for each of the modeled reactor regions contributing material to the discharge. Hence, the uncertainty in DPP, modeled reactor region power, and number of tons in the push were used as appropriate multipliers to perturb the nominal values of these quantities.

The iodine content of each discharge in Ci of iodine-131 per ton was calculated using Equation 4.3. The calculation involves DPP, ECT, and LOAD as multipliers of P, the pile power in Equation 4.3.

The following is a listing of the distributions for these parameters in RM and their technical basis:

DPP: A uniform distribution centered on 1.0 with a range of ±5%. This represents the measurement uncertainty in pile power. The pile power is based on a simultaneous measurement of pile coolant flow rate, inlet temperature, and outlet temperature. The equation is:

$$\text{Power (MW)} = 0.2635 \times \text{Flow (KGPM)} \times (T_{outlet} - T_{inlet}) \qquad (4.5)$$

where the temperatures are in degrees Celsius. Typical uncertainties for both flow and temperature measurements were less than 5%. Hence, combined product uncertainty of 5% is a reasonable estimate.

62,63 ECT: The P-Department Reports (General Electric Company 1947) include a daily quotient of pile power divided by the average power of usually the ten highest-powered tubes in the pile. This was called Effective Central Tubes or ECT. If the distribution of power within the pile were completely uniform, then all tubes would have the same power, and ECT would equal the number of physical tubes. Indeed, the radial power PF is the ratio of physical tubes to ECT. Thus, the ECT number is a daily measure of the radial power peaking in the pile. The daily variation in this number is estimated to be within 10% based on the author's personal experience of daily Hanford reactor operations. Specific reports addressing this subject were *never* written because it was not considered pertinent; hence, firmer references were not located. *A* uniform *distribution* with a ± 10% range *was selected for ECT.*

LOAD: The P-Department Reports did not log the pile loading. However, a pile inventory was estimated from the records of material charged and discharged. The possibility that there could be some error because of the required interpretation of the recorded number of slugs charged and discharged led to an estimate of ±3% for this uniform distribution.

PUSH: The number of slugs in each push was given directly in the P-Department Reports (General Electric Company 1947). Accounting errors were judged to be in the ±1% range. A uniform distribution with this range was, therefore, used.

4.2 DECAY OF IODINE-131 FROM DISCHARGE TO DISSOLUTION

64 From December 1944 through May 22, 1946, the reconstruction of dissolver operations was based on the 200 Area Reports (Acken and Bird 1945; Bird and Donihee 1945). These reports did not specify the reactor pushes being dissolved, but the cut identification indicated the reactor of origin. The standard dissolver charge was 840 slugs or 3.3 tons (840 slugs x 7.85 lb/slug x 1 ton/2000 lb = 3.3 tons). A queue of oldest-fuel-first, based on P-Department Reports *of* pushes and guided by the Jaech (undated) listing of monthly pushes dissolved at each plant, was set up, and 3.3-ton charges from this queue were loaded into the dissolver to match the pattern of indicated transition points. These were cases in which pushes from one reactor changed

to pushes from another reactor. In some instances it was necessary to change the 3.3-ton charge to meet the indicated transitions, as no doubt occurred in actual operation. This strategy was followed until May 22, 1946, when the information source stopped.

4.2.1 Plant Operation

The following is an account of the reconstructed operations at T and B Plants.

December 1944 and January 1945

Before December 26, 1944, unirradiated uranium slugs had been used in test runs of the dissolving operation. In addition, slightly irradiated uranium received from Oak Ridge ("Clinton Tracer" material) and 32 slugs from B Reactor, discharged on November 7, 1944, at 16 MWd/ton (General Electric Company 1947), were dissolved. These dissolver runs on inactive material are shown in detail in a table at the bottom of page 64, Hanford Technical Manual (Dupont 1944). The first dissolution of active metal discharged from B Reactor occurred at T Plant on December 26, 1944 (Dupont 1946, pg 45). Acken and Bird (1945) show that the dissolver batch designation for the December 26 dissolution was T-4-12-B5 (I plant, 1944, Month 12, B reactor material, 5th cut of the month). The material dissolved in prior cuts did not contain significant amounts of iodine-131 because it was either completely unirradiated, or *experienced* such a low level of irradiation that the iodine-131 content was insignificant compared to the material dissolved on December 26.

The amount of material dissolved in the three December cuts (T-4-12-B5, T-4-12-B6, and T-4-12-B7) was 3.5 tons, as shown in the table at the bottom of page 62 in West (1945). The information in the table indicates that 3.5 tons of irradiated uranium was shipped from the 200 N interim storage area to 200 Area Separations on December 23. The next shipment of 3.7 tons was not received until December 30, according to the next table entry. This material was dissolved in January 1945.

52 The 3.5 tons would be 892 slugs (7.85 pounds per slug [Dupont 1944]), which is slightly larger than what was to become the standard 840-slug dissolver charge (8 buckets of 105 slugs each). The "heel" would comprise relatively inactive material left over from the previous cuts. The combined December shipments from 200 N Area are 3.5 tons and 3.7 tons for a total of 7.2 tons. This is confirmed in part by the Jaech reference (undated), which shows a subtotal of 7.22 tons. Bird and Donihee (1945) show that three cuts were made on January 1, 1945. Therefore, the three cuts must have come from all 3.7 tons from the December 30 shipment. West (1945) states that another shipment of 0.7 tons left 200 N on January 13, 1945. Jaech (undated) states that 7.22 tons and 0.74 tons were dissolved in January 1945. Bird and Donihee (1945) and West (1945) are clear that 3.5 tons of this were indeed dissolved in December, and that the 3.7 tons shipped on December 30 were dissolved on January 1, 1945. The total January shipments from Jaech (undated) are 7.22 + 0.74 = 7.96 tons. The P-Department Reports (General Electric Company 1947) state that 2048 slugs were discharged during the outage that started on November 29, 1944. That would be 8.04 tons. In this case, a total of 7.96 tons from the November 24, 1944, push from Jaech (undated) contrasts slightly with the 8.04 tons from the P-Department Reports. In reconstructing the amount of material dissolved, the amount of material listed in the P-Department Reports (General Electric Company 1947) is taken as the primary source in all cases. In the present case, the 0.74 tons from the Jaech reference (undated) is increased to 0.82 tons to match the 8.04 tons of November 24 push from the P-Department Report:

Jaech (undated): 7.22 + .74 = 7.96.

HEDR reconstruction:

3.50	dissolved December
3.72	dissolved January
0.82	dissolved in February
8.04	Total for 11/24/44 push.

February 1945

52,65 Jaech (undated) states that 5.8 tons were dissolved in six cuts from the push 12/20/44. The P-Department Reports (General Electric Company 1947) list

1947) list 1536 slugs discharged or 6.03 tons from this push. *In* the HEDR reconstruction *it was* concluded that 6.03 tons were dissolved from this push plus the 0.82 tons left over from the 11/24/44 push. The first dissolver charge was 3.425 tons of mixed 11/24/44 and 12/20/44 material and a second charge of 3.425 tons of pure 12/20/44 material followed. The dates of dissolution are taken from Acken and Bird (1945) and Bird and Donihee (1945) for this and all subsequent cases.

March 1945

66 According to Jaech (undated), 6.57 tons from the 1/18/45 push were dissolved in six cuts. The P-Department Reports for this push show 6.67 tons discharged (1699 slugs). Acken and Bird (1945) corroborate this and provide dates for the six cuts. Accordingly, *in* the HEDR reconstruction *it was* concluded that 6.67 tons were dissolved in two charges of 3.335 tons each. By March, dissolver operation was approaching the standard charge of 3.3 tons (840 slugs).

April 1945

The startup of B Plant in April is documented in Dupont (1946) on page 65, "The first dissolving of active metal in B Plant was made on April 13, 1945." In the last paragraph on this page it states, "In starting T Plant, this heel was built-up with reject, inactive metal. In the B Plant start-up, where no inactive metal runs were made, it was necessary to use active pile metal for the heel. Similarly, in June 1945, when a second dissolver was placed in operation in both plants, both heels were built up of active metal." This means that either each dissolver received an initial charge of 4.4 tons, and acid was added to dissolve only 3.3 tons in three cuts of 1.1 tons each, or that a standard 3.3-ton charge was loaded and only 2 cuts were taken. Acken and Bird (1945) and Jaech (undated) show B-5-04-B11 as the last cut of the month, which would indicate that nine cuts were dissolved in the standard way and two cuts were taken from the first push dissolved (2/22/45 B). Since D Reactor fuel was now being dissolved for the first time, pushes will be identified by date and a letter indicating the reactor of origin (B, D, or F).

The four pushes were processed both at B and T Plants according to Jaech (undated), which provides information on what part of each push went to the two separations plants. This was adjusted slightly to agree exactly with the P-Department Reports (General Electric Company 1947) discharge total. Nearly all estimates of the charge makeup are close to 3.3 tons throughout the month, indicating excellent agreement between the three primary references: General Electric Company (1947), Acken and Bird (1945), and Jaech (undated).

May 1945

As in April, agreement is good between primary sources, and the charge makeup is only slightly above the 3.3-ton standard. There is an apparent error in the 200 Area Weekly Reports (Acken and Bird 1945) in the designation of T Plant cuts B_d-4, 5, and 6. Jaech (undated) shows that 3.31 tons of push 3/28/45 D were dissolved during the month. Later on in the month Jaech (undated) indicates there were six cuts, D_d-13 through D_d-18, taken from 6.68 tons of 4/19/45 D. (The tonnages are adjusted slightly to agree exactly with P-Department Reports [General Electric Company 1947] records: 3.31 to 3.34 and 6.68 to 6.69 for the HEDR reconstruction.) In order of processing at T Plant, 3/22/45 B would be the first batch reprocessed (cuts B_d-1, 2, 3), then 3/28/45 D should be next, but the next three batches are designated B_d-4, 5, 6 instead of D_d-4, 5, 6. The HEDR reconstruction (Table 6.1 and 6.2, Volume II) reprocessed the D fuel at this point, but retained the 200 Area Weekly Report (Acken and Bird 1945) cut designations.

June to December 1945

At B Plant, the amount charged to the dissolvers in the HEDR reconstruction varied from a low of 3.17 tons to a high of 3.43 tons, with all changes in the reactor source of the push made as indicated by the cut identification from Bird and Donihee (1945). At T Plant, the reconstructed amounts charged varied from 3.25 to 3.49 tons with the exception of the period 12/12/45 to month end, when the available spent fuel dictated that an average charge of only 2.94 tons could be maintained.

During September, an attempt to sort slugs on the basis of burnup was made in an effort to isolate lower-exposure fuel for reprocessing (West 1945).

The procedure monitored the gamma activity with an underwater ionization chamber to identify slugs that had occupied the center section of the process tube during their in-pile residence. No accounting of this material was made in the records that were recovered. These segregated center slugs would have a higher-than-average iodine-131 content. To account for the possibility that higher iodine-131 releases may have occurred during September, a larger uncertainty was assigned to batches dissolved in September.

A campaign of processing high burnup material, obtained by delaying discharge of selected tubes until the average exposure neared a goal of 400 MWd/ton, was initiated at T Plant during the months of December 1945 through March 1946. This is established by burnup calculations based on P-Department Reports. Curiously, Jaech (undated) shows burnups for this material in the normal range (around 200 MWd/ton). Here again, the reactor records are considered to be of higher quality and are the source of discharges used in the HEDR reconstruction. The higher discharge burnup of this material was obtained by extending the in-pile residence time and by selecting high-powered tubes. Slugs from these tubes had a larger-than-average iodine content. This is accounted for in the reactor model, which selects higher-powered tubes to obtain the required discharge goal burnup of 400 MWd/ton.

January 1946

The reconstruction of T Plant operations during the month was entirely regular with all dissolver charges of 3.3 tons and the pattern of pushes indicated in Bird and Donihee (1945) duplicated.

At B Plant, not enough eligible material, as indicated by the P-Department Reports, was found to supply the 21 cuts (F_d-7 through F_d-27) indicated in the 200 Area Weekly Reports (Bird and Donihee 1945). This was compounded by an apparent over-abundance of push 12/04/45 B that followed the F cuts. There were nine cuts marked from B Reactor, but this push was 13.6 tons, slightly over 12 cuts at the standard 1.1 tons per cut. The last three cuts from F, F_d-25, 26, and 27, were loaded with B Reactor fuel from the 12/4/45 push, and the 21 F cuts were light loaded at 2.95 tons per charge instead of the standard 3.3-ton charge. This solved both problems of the apparent paucity of F fuel and the over-abundance of B fuel. Although no

anecdotal references were found to support this reconstruction stratagem, it is quite within the scope of normal operations that more than three cuts per charge were made to lower the amount of heel in the dissolvers without any special note being made (Acken and Bird 1945; Bird and Donihee 1945). This would lower the amount per cut and would be equivalent to light charging and taking three cuts as far as the amount of fuel dissolved is concerned. It would also preserve enough F fuel (only a few slugs would be enough) to cause the last three cuts to be labeled as F fuel when the bulk of the charge was, in fact, made up of 12/04/45 B fuel.

February through April 1946

The reconstruction of T and B Plant operations was regular during this period with the charge ranges of 3.22 to 3.31 at T Plant and 3.29 to 3.56 at B Plant.

May through August 1946

The 200 Area Weekly Reports (Bird and Donihee 1945) stop during the month of May with the last entry on 5/22/46. The reconstruction then depends on information from Jaech (undated). This provides a monthly summary of the pushes and the amount from each dissolved each month at T and B Plants. As stated before, this reference actually supplies the energy generated in the fuel of each push as well as the average burnup of the discharge, hence the tons discharged are calculated by dividing energy by burnup. Also as before, the amount of each push dissolved is balanced exactly with the amount discharged as given in the P-Department Reports (General Electric Company 1947).

Unfortunately, there is no information given on the day of the month when dissolving occurred until the Metal History Reports (General Electric Company 1946) begins on 8/17/46. During this "blank period," a monthly average spacing (days per cut) was used. This was made possible because Jaech (undated) gives the final cut of the month, which established the number of cuts taken during the month. The spacings used are shown in Table 4.1.

67,68 B Plant averaged more than one cut per day, while T Plant was less than one cut per day. To assign cuts to days by a uniform method for both plants, an integer round-off technique was developed. *The number of cuts in a month*

TABLE 4.1. T and B Plant Average Days Per Cut for the Blank Period 5/22/46 Through 8/20/46

Month	Cuts	Days	Days/Cut	Start Cut	End Cut	Start Date	End Date
B Plant							
May 46	19	10	0.52632	D_d-35	Fd-53	05/22	05/31
June 46	42	30	0.71429	F_d-54	Dd-41	06/01	06/30
July 46	44	31	0.70455	D_d-42	Dd-43	07/01	07/31
Aug 46	45	24	0.53333	D_d-44	Dd-37	08/01	08/24
T Plant							
May 46	5	10	2.0000	B_d-26	B_d-30	05/22	05/31
June 46	21	30	1.4286	F_d-1	D_d-21	06/01	06/30
July 46	26	31	1.1923	D_d-1	F_d-26	07/01	07/31
Aug 46	1	1	1.0000	F_d-26	F_d-27	08/01	08/01

plus one were divided by the number, N, of days in the month to give an integral number of cuts per day plus a fractional remainder. The days in the month were indexed from 1 to N. The fractional remainder of the average cuts was summed from 1 to N. Every time the sum crossed an integer, that day had a cut added to it. This gave a reasonably uniform pattern of days that had two cuts for B Plant, and days that had zero cuts at T Plant. It also gave the correct total number of cuts per month. At T Plant, the range of the uniform distribution function representing the uncertainty of the cooling time (DCT) was increased from ±1 day to ±2 days during this period to reflect the uncertainty in date of dissolution.

At T Plant, a special situation occurred in August. There were only six cuts taken according to Jaech (undated). The Metal History Reports (General Electric Company 1946) shows that the first of these, F_d-1, was in extraction (the step following dissolving and storage) on August 20.

An average period of 3 days is assumed for the lag between dissolution and extraction (as will be discussed shortly). This means that F_d-1 would have been dissolved on August 17. This effectively terminates the blank period for T Plant (i.e., all subsequent dates of dissolution will be taken

from the Metal History Reports [General Electric Company 1946]). Jaech (undated) lists F_d-26 as the last cut of July. Assuming that three cuts per charge were taken, there must have been an F_d-27, which would have been dissolved in August and was not included in Jaech (undated). It was assumed that it was dissolved on August 1 because date spacing in July had been running at one per day.

4.2.2 Distribution Functions

The distribution functions reflecting uncertainty in the dissolver operations and iodine-131 content in STRM are described below.

Defining C(I) to be the number of curies of iodine-131 in some particular dissolver cut I, STRM first calculates C(I) based on the nominal values of the parameters. It then proceeds to calculate a possible number of curies CP(I) for the current Monte Carlo realization where an N has been added to the name of the distribution being sampled to indicate the value which resulted from sampling that distribution (i.e., DCTN is the value obtained from sampling the DCT distribution):

$$CP(I) = e^{-LAMBDA \cdot DCTN} \cdot C(I) \cdot PHYSICSN \cdot MASSN(I)$$

The sampled variables are:

DCTN = Delta Cooling Time, a positive or negative number of days sampled from the DCT distribution expressing the uncertainty in the cooling time.

53.69 PHYSICSN = A multiplier which expresses the uncertainty in the constant *24,174* in Equation 4.3 because of the *uncertainty* in the nuclear parameters energy per fission (MeV/fis) and iodine-131 fission yield. It is the result of sampling the PHYSICS distribution.

MASSN = A multiplier which expresses the uncertainty in the number of tons dissolved. It results from sampling the MASS distribution.

LAMBDA = The decay constant of iodine-131. This is constant at 0.0862. It is not sampled (i.e., it is assumed known without error).

The amount released, AP(I), is calculated as the product of CP(I)·RFACN, where RFACN is a release factor that results from sampling the RFAC distribution.

54.70 After AP(I) is calculated, a further set of sampled variables is used to determine the release timing for a particular Monte Carlo pass. The *duration of* dissolver cut I, *denoted* TD, is TD = 8 + DLENGTHN *(see Table 4.2 for definition)*. DLENGTHN is a positive or negative integer, which results from sampling the DLENGTH distribution. The nominal dissolving time is 8 hours (Lindvig 1945 and 1946).

55 The fraction of AP(I) released during the Jth hour of dissolving (J=1, DLENGTHN) is FAP(I,J). FAP(I,J) = PROFILEN(DLENGTH,J)·AP(I), where PROFILEN is a fraction that results from sampling the PROFILE(DLENGTH,J) distribution. The PROFILE(*I*,J) is a set of distribution functions built into STRM. The sum of PROFILE(*I*,J) over J=1, DLENGTH is normalized to unity to preserve AP(I), the number of released curies of iodine-131.

Having determined the hourly releases, the timing of the release is then determined. Some of the start times are known and, in a few cases, the stop times are also known. When both are known, DLENGTH is not sampled. When only the start time is known, it is used and the sampling regime is carried out. From December 1944 through May 1946, the timing information comes from the 200 Area Weekly Reports (Acken and Bird 1945; Bird and Donihee 1945). This reference reports on the cuts in the dissolver at 8 a.m. If a particular cut is reported to have gone out of the dissolver from one day to the next, it must have completed dissolving on day shift (8 a.m. to 4 p.m.) of the first day or on swing shift (4 p.m. to midnight) or graveyard shift (midnight to 8:00 a.m.) of the following day. In that case, all shifts are considered equally probable, and a uniform distribution covering the integer range from 1 to 3 is sampled. After June 1945, because of more favorable atmospheric conditions, dissolving on day shift was prohibited (Dupont 1946). This reduces the choice to two shifts: swing and graveyard. In this case, a uniform distribution covering the integer range from 1 to 2 was sampled.

In a few instances, two cuts shown in the dissolving stage are not there on the next day. In that case, the first one was assumed to be dissolved on

swing and the other on graveyard if it occurred after day shift dissolving was prohibited. If daytime dissolving was permitted, then a choice between days and swing is made by sampling a uniform distribution with a range of 1 to 2. If days is selected, then another uniform 1 to 2 sampling is made to select either swing or graveyard. If swing is selected, then the other cut is dissolved on graveyard.

After the shift is selected by input or by the sampling technique, the within-shift timing (SHIFTHRN) is determined by sampling from the SHIFTHR distribution.

After August 17, 1946, the principal sources of dissolving information are the Metal History Reports (General Electric Company 1946). This source gives the date of cut entry into the extraction step of the bismuth phosphate separation process. This step follows dissolving. It was necessary to develop a distribution for the number of days between dissolving and extraction. This is the LAG distribution. A nominal value of 3 days is subtracted from the extraction date to determine a nominal dissolving date. The time of dissolution for a given Monte Carlo realization is calculated by algebraically adding LAGN to the nominal dissolving date, where LAGN is the result from sampling the LAG distribution.

Not all the iodine-131 is released to the dissolver off-gas line, as explained in Section 1.3.1. There the effective release fraction is given by $RF_{EFF} = RF_1 - RF_2 + RF_3$, where RF_1 is the fraction released to the off-gas line, RF_2 the fraction of condensate collected at the stack bottom, and RF_3 the fraction remaining in solution and released during subsequent processing steps. RESIDUAL is the distribution that models the uncertainty in RF_3.

The remaining distribution is HU, the heel uncertainty. In the DOI module, a constant 1.1-ton heel is assumed (i.e., 1.1 tons of each fresh charge remains after the specified number of cuts plus current heel are dissolved). During a Monte Carlo realization in STRM, this nominal 1.1-ton heel is varied by sampling an amount HUN from the HU distribution:

HEELN = 1.1 + HUN, where HEELN is the mass of heel for run N.

The distributions are summarized in Table 4.2. The specific distributions selected are described below:

DCT: Delta cooling time is a uniform distribution from -1 to +1. Sampling interval is every cut. This is the uncertainty due to whole-day representation of push date and dissolving date. At most, this could add or subtract a 1-day interval between the push and dissolving time. For example, using this diagram:

```
x----|----x----|----x----|----x----|----x
0         1         2         3         4
   Day 1     Day 2     Day 3     Day 4
```

TABLE 4.2. Sampled Variable Summary

VAR	Variable Description
DCT	Delta Cooling Time, returns whole number of days around nominal cooling time. Additive; that is, if it returns a zero, it uses the nominal.
RFAC	Release Factor, returns a factor. If 1.0, it uses the appropriate input value, RFAC(I).
SHIFT	Shift dissolving starts.
DLENGTH	Length change from the nominal 8-hour dissolving period in hours.
SHIFTHR	Delay in dissolving after shift start, in hours.
PROFILE	This is a routine that allocates the iodine released in each cut to the specific hour of the dissolver run.
PHYSICS	Variation in basic physical constants, Mev/fission, and iodine-131 fission yield, which are contained in the constant 24174 of the basic iodine equation.
MASS	Amount of fresh charge and heel dissolved in each cut. This is a multiplier on the nominal mass dissolved.
HU	Heel Fraction. This is an additive quantity which varies the nominal 1.1-ton heel.
LAG	Elapsed time between dissolving and extraction. It is necessary because one separation plant reference (General Electric Company 1946) gives the time of extraction, not dissolution.
RESIDUAL	The fraction of dissolver iodine-131 not in the dissolver off-gas, which escapes during post-dissolution processing over a 4-day period.

Whole-day accounting would call this a 3-day interval. Mid-day center line on day 1 would be subtracted from the mid-day 4. If the push occurred slightly after 0 and the dissolving slightly before 4, then the maximum actual interval would be 4 days. If the push occurred slightly before 1 and the dissolving occurred slightly after 3, then the minimum interval would be 2 days. Since there is no additional information on the distribution, a uniform distribution is used. With an 8-day half-life, the 2-day uncertainty range in iodine-131 concentration is 16% because of this distribution.

In the period from mid-May through the end of May 1946, at T Plant after the last information from the 200 Area Weekly Reports (Bird and Donihee) stop, production was at the rate of approximately one-half cut per day. Assuming a uniform rate, this adds an additional day to the uncertainty. For this period at T Plant the range of the uniform distribution is increased from ±1 to ±2 days.

SHIFT: Shift that dissolving occurred. The 200 Area Weekly Reports (Acken and Bird 1945; Bird and Donihee 1945) give a cut status report as of 8 a.m. each day. If a particular cut is shown as "dissolving," then that cut was at least loaded into the dissolver. Nothing more is known; that is, it may have been just loaded, in the cladding removal stage (no iodine-131 in the off-gas), or actively dissolving. However, when the same cut is shown as "in extraction" for the following day, then dissolution was definitely completed during the 24-hour interval. This leaves three logical possibilities: day shift, swing shift, or graveyard of the following day. This situation is designated DSG. An equally probable sampling is then done on these three shifts. In many cases the situation may be improved upon. For example, beginning in June 1945 there was a prohibition on daytime dissolving (Dupont 1946, p. 67). Therefore, DSG is reduced to SG during this period. Another situation exists when more than one cut was dropped from dissolving. Since only one cut could be dissolved at a time, two cuts dissolved would mean that the first one would be designated DS and the next one SG. Or, if it occurred when day shift dissolving was prohibited, then the first cut would be on swing shift and the other on graveyard. Each cut is assigned a shift designator (D, S, G, DSG, SG), and an equally probable choice is made between the available logical possibilities subject to selection rules. That is, for a DS-SG set of possibilities, if D is selected for the first cut, then the selection for the second one is still SG, but if S is selected for the first one, then G is simultaneously selected for the second one, etc.

56

DLENGTH: Variation in the length of dissolution around the 8-hour nominal is a triangular distribution with a range of ±4 *hours* centered on 0.0. This variable is sampled for each cut. The

basis for this is a set of 15 stack gas activity profiles from the Health Instruments Department Logbook, HEW-823-L (Lindvig 1946). The data is summarized below in two different ways:

Bin 1 (hr)	Number in Bin	Bin 2 (hr)	Number in Bin
0.0-6.0	3	0.0-6.0	3
6.0-7.0	2	6.0-8.0	7
7.0-8.0	5	8.0-10.0	3
8.0-9.0	1	10.0-12.0	2
9.0-10.0	2		0
10.0-11.0	1		0
11.0-12.0	1		0
Total	15		15

Because these are both peaked distributions, a triangular distribution was selected. The range of ±4 hours was chosen to match the PROFILE distributions, which cover the range of 4 to 12 hours in 1-hour increments. The range choice is consistent with the variation that might occur with such a small sample size.

SHIFTHR: The starting hour of dissolving within a shift, which is added to the starting hour of the shift, is a triangular distribution with a minimum at 0.0, mode at 1 and maximum at 3, sampled at every cut. This distribution is used, along with DLENGTH, to express the uncertainty in timing of the dissolver operation. In qualitative terms, it is certain that all dissolving did not start in the first hour of the shift. In order to complete the operation within the 8 hours, a long delay would have been infrequent. The triangular distribution chosen limits the delay to 3 hours (i.e., before mid-shift) and provides some variability in the dissolving start times.

PROFILE: This not a distribution function, but rather a sub-routine that selects from a group of distribution functions. Its function is to allocate a fraction of the total iodine-131 released in each cut to each hour of the dissolving run. The basis for this is an analysis of 17 measured profiles of stack gas

activity from the Health Instruments Department Logbook, HEW-823-L (Lindvig 1946). Figure 4.1 is a plot of all 17 runs. The actual time during the run is normalized so that all run profiles may be compared.

71 The data are divided into fractions for analysis. For a 4-hour run, the data set is divided into four equal fractions. A distribution function is determined for each of the four fractions. A 5-hour run is divided into fifths and a set of five distribution functions determined, etc. This procedure produced 13 sets of distributions for dissolver runs from 4 to 16 hours in length. Of these, only nine were required to cover the 4- to 12-hour range resulting from the DLENGTH distribution. *The data in each division were plotted and a form for the distribution function selected. Where a triangular distribution appeared to represent the data best, a maximum likelihood technique was used to determine the range and mode.*

Two additional criteria were applied to candidate profiles from this process.

1. No up-turned ends. The fraction selected for the second period had to be greater than the first period, and the next-to-last had to be greater than the last.

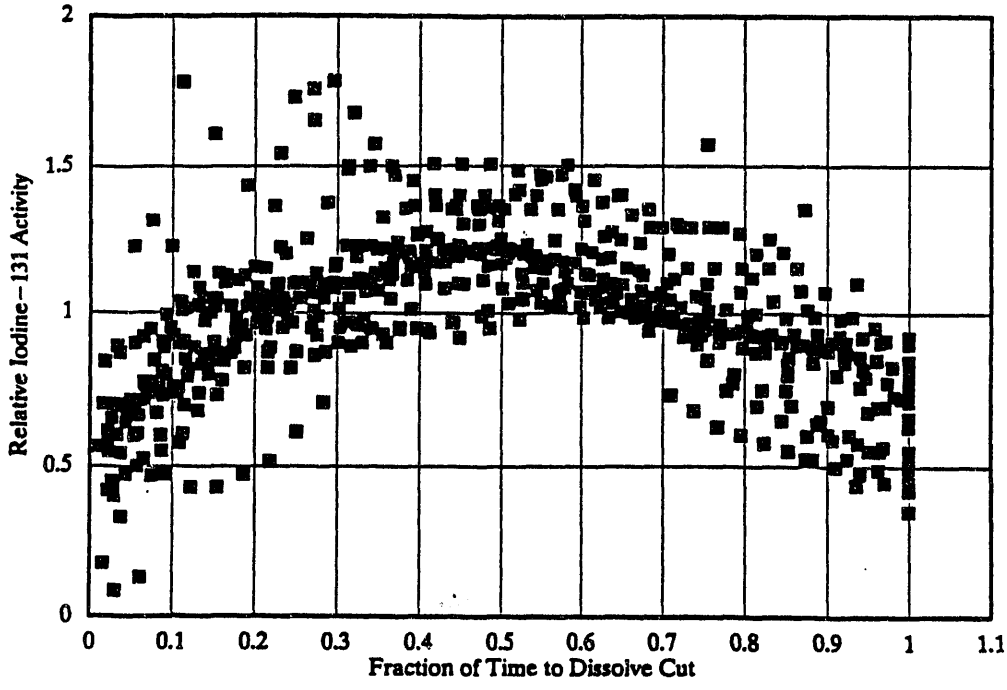


FIGURE 4.1. Relative Iodine-131 Activity During Cut

57 2. Smoothing. Successive values could not *change by* more than one half the mean value. For example, for a 4-hour run, each successive fraction would have to be within 1/4 x 1/2 = 1/8 of the previous value.

58 Sampled sets not meeting these criteria were discarded and sampling was repeated. *For each realization, the selected values true of PROFILE (I,J) were divided by* Σ_1 *PROFILE(I,J).* Figure 4.2 shows results from 100 runs for a 16-hour duration profile, chosen for illustrative purposes because it provides more intervals. The broad features of the original data are reproduced: the composite profile tends to be convex upwards, and the ranges mimic the original data ranges fairly well. The functions are shown in Table 4.3.

PHYSICS: Uncertainty in principal physical constants of iodine-131 equations was represented by a piece-wise uniform distribution approximating a normal distribution centered on 1.0 with a standard deviation of 0.05. One-sixth of the area was between 0.9 and 0.95, two-thirds of the area between 0.95 and 1.05, and one-sixth between 1.05 and 1.1. This distribution is sampled by Latin Hyper Cube at the beginning of each Monte Carlo realization because it is not considered to vary with each dissolver cut. The basis of this is the uncertainty around the measured energy per uranium-235 fission of 201.72 Mev (Croff 1980), and

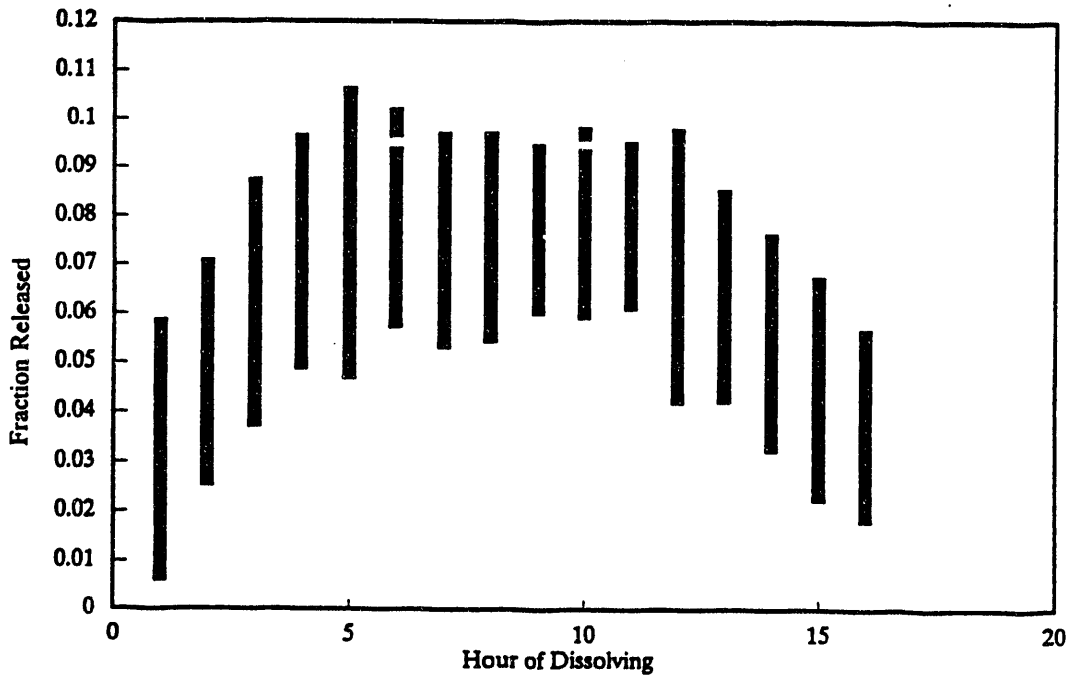


FIGURE 4.2. Modeled I-131 Release Profile: 16-Hour Cut

TABLE 4.3. PROFILE (L,J) the Distribution Functions for Hourly Release Allocation

L	J	Min	Mode	Max	L	J	Min	Mode	Max
4	1	0.083	0.242	0.316	9	1	0.018	0.103	0.120
4	2	0.219	0.277	0.389	9	2	0.045	0.108	0.169
4	3	0.250	0.251	0.363	9	3	0.081	0.106	0.200
4	4	0.121	none	0.272	9	4	0.094	0.135	0.167
5	1	0.057	0.166	0.261	9	5	0.103	0.124	0.174
5	2	0.187	0.188	0.329	9	6	0.111	0.111	0.167
5	3	0.186	0.232	0.308	9	7	0.074	0.110	0.155
5	4	0.163	0.200	0.272	9	8	0.052	0.101	0.143
5	5	0.085	none	0.226	9	9	0.042	none	0.110
6	1	0.043	0.131	0.214	10	1	0.018	0.072	0.108
6	2	0.106	0.161	0.275	10	2	0.037	0.099	0.160
6	3	0.144	0.203	0.249	10	3	0.060	0.098	0.176
6	4	0.167	0.174	0.252	10	4	0.094	0.094	0.160
6	5	0.104	0.165	0.224	10	5	0.087	0.121	0.156
6	6	0.063	none	0.184	10	6	0.100	none	0.149
7	1	0.033	0.108	0.177	10	7	0.099	0.100	0.143
7	2	0.071	0.146	0.227	10	8	0.059	0.097	0.139
7	3	0.123	0.156	0.225	10	9	0.045	0.075	0.135
7	4	0.131	0.171	0.220	10	10	0.034	none	0.099
7	5	0.142	0.143	0.206	11	1	0.014	0.065	0.096
7	6	0.079	0.134	0.189	11	2	0.033	0.080	0.153
7	7	0.053	none	0.150	11	3	0.047	0.090	0.154
8	1	0.027	0.093	0.148	11	4	0.083	0.083	0.155
8	2	0.055	0.124	0.188	11	5	0.077	0.111	0.139
8	3	0.116	0.116	0.213	11	6	0.083	0.109	0.141
8	4	0.108	0.151	0.194	11	7	0.088	none	0.136
8	5	0.125	none	0.185	11	8	0.077	0.091	0.128
8	6	0.104	0.124	0.177	11	9	0.051	0.087	0.122
8	7	0.063	0.114	0.162	11	10	0.038	0.060	0.124
8	8	0.043	none	0.126	11	11	0.031	none	0.089
					12	1	0.011	0.059	0.086
					12	2	0.029	0.072	0.144
L = length of cut index (hr)					12	3	0.039	0.082	0.136
					12	4	0.070	0.071	0.150
J = hours into the cut					12	5	0.070	0.099	0.127
					12	6	0.073	0.100	0.130
All distributions are triangular except those with none as the mode. Those are uniform with minimum and maximum ranges shown.					12	7	0.083	none	0.124
					12	8	0.080	0.086	0.123
					12	9	0.058	0.085	0.120
					12	10	0.044	0.078	0.111
					12	11	0.028	0.077	0.107
					12	12	0.027	none	0.082

the uncertainty around the measured value of the iodine-131 fission yield of 0.0289. These experimentally determined quantities are typically known within a 5% range.

59 MASS: Uncertainty in the mass of freshly charged fuel dissolved in each cut is represented by a triangular distribution, with a minimum of 0.939, mode of 1.0, and a maximum of 1.121. For a standard dissolver charge of 3.3 tons, the minimum would be 3.3 x 0.939 = 3.10 tons, the mode would be 1.0 x 3.3 = 3.3 tons, and the maximum would be 1.121 x 3.3 = 3.70 tons. The distribution applies to the period from December 1944 to May 1946 and relies on the 200 Area Weekly Reports (Acken and Bird 1945; Bird and Donihee 1945), which do not provide the mass of uranium for each dissolver charge. The charge mass is assumed to be the nominal 3.3-ton (840-slug) dissolver load, provided that this fits the available fuel pushes from the reactors. In general, the available backlog is worked off under the 3.3-ton charge assumption. However, during certain periods the standard load was changed slightly to fit the available fuel supply and the pattern of reactors of origin in the record. The reconstructed average dissolver charge for 207 charges is 3.306 with a standard deviation of 0.095 tons at B Plant, and a 3.291-ton average with a standard deviation of 0.087 tons at T Plant for 151 charges. Some 14 low-weight charges (2.57 tons) at T Plant have been removed from the T Plant figures because the uncertainty here is higher and requires another distribution to express it. Figure 4.3 is a plot of the number of charge weights in each range. The plot shows that a skewed triangular distribution with minimum, mode, and maximum of 3.1, 3.3 and 3.7 is a good description of the uncertainty in the reconstructed dissolver charges.

In the period May 5, 1946, through June 26, 1946, T Plant dissolved 14 charges, which were mostly from B Reactor discharges made after B Reactor was shut down; it did not resume operation until after 1947. It was necessary to "light load" the dissolvers with 2.57-ton charges to have the number of cuts match during this period (i.e., there was not enough fuel to match the number of cuts in the record). The records did not explain the cause of this discrepancy. This makes it necessary to increase the uncertainty during this period. Accordingly, the range on the triangular distribution was increased to 0.667 minimum, 1.0 mode, and 1.242 maximum. The range in tons is 0.667 x 2.57 = 1.71 tons minimum to 1.24 x 2.57 = 3.19 tons maximum. No objective basis exists for this choice; however, it does retain the skewed shape based on many samples and reflects the qualitative judgment that not enough is known about the actual dissolver operation in this period. B Plant did not process this material, hence it was not necessary to use the broadened distribution.

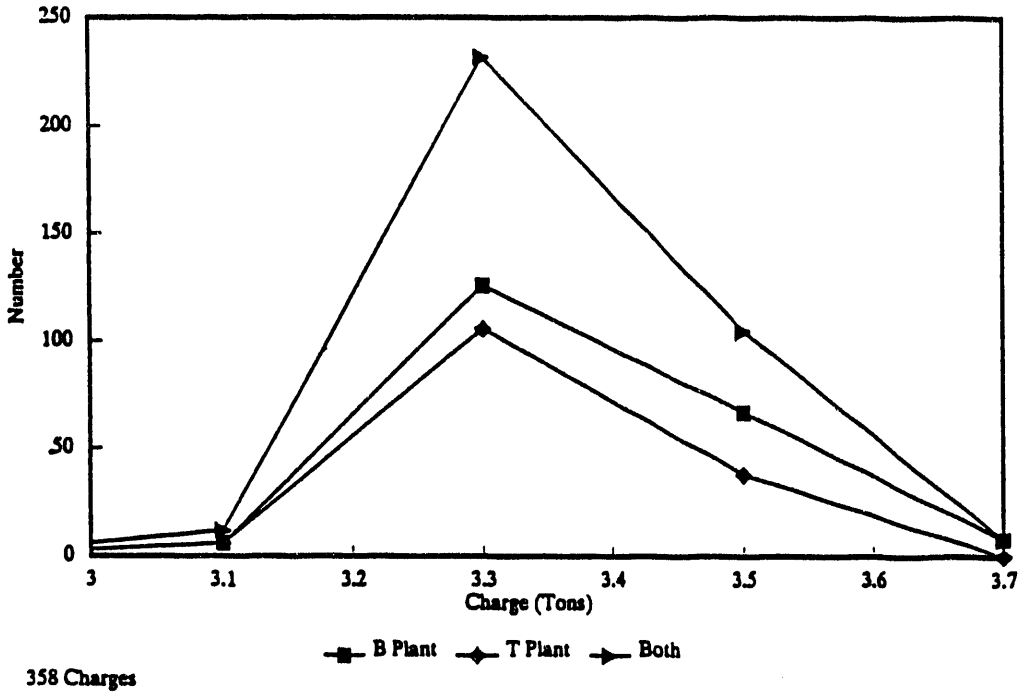


FIGURE 4.3. HEDR Construction of Dissolver Charge Weights

After August 17, 1946, the Metal History Reports (General Electric Company 1946) do give the number of slugs charged. For this period, a normal distribution is used with a standard deviation of 0.015, which models the slight errors in the recorded number of slugs.

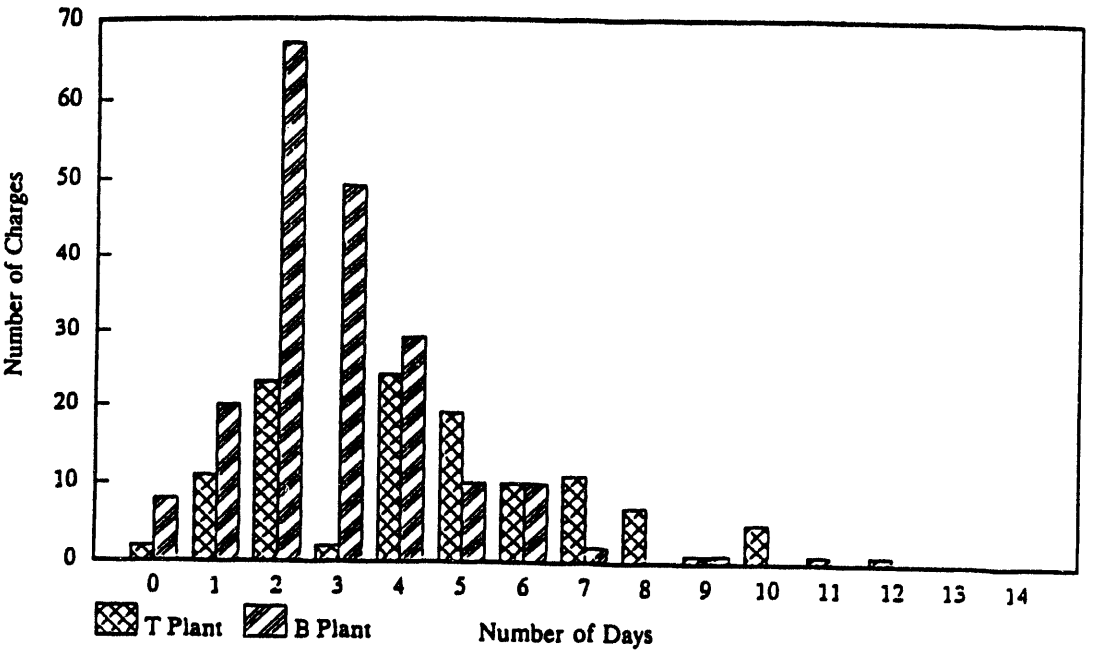
HU: Heel uncertainty is the variation in the 1.1-ton assumed standard heel mass. A triangular distribution with a minimum value of 0.9 ton, a mode value of 1.1 tons, and a maximum value of 1.22 tons was used. The true heel was virtually undeterminable. However, in nearly 1980 cuts for both T and B Plants, two cuts were made from the 3.3-ton charge to build up the heel on only two occasions, and four cuts were taken to lower the heel only once. This indicates that the variation must have been small and random; otherwise, these departures from the standard procedure would have been more frequent.

LAG: The elapsed days between the dissolving and extraction steps takes a triangular distribution with the minimum at 0 days, mode at 3 days, and maximum at 7 days. This distribution is only used for the August 1946 to December 1947 time period where the principal references are the Metal History Reports which, regrettably, do not give the day of dissolving but do give the day of extraction (General Electric Company 1946).

Figure 4.4 shows a histogram of 340 cuts for which the lag time was determined. This forms the basis for the triangular distribution. The average lag for all plants was 3.4 days. The mode was put at 3 days, the nearest integer days because the calculations are based on integer days. The figure shows an upper value skewness (i.e., -3 days to +4 days) around the 3-day mode. The few batches above 7 days probably reflect plant outages for maintenance and repairs, and should not be included in a distribution intended to reflect normal process variation.

4.3 THE RELEASE OF IODINE-131 TO THE AIR

The iodine-131 release fraction is defined as the ratio of iodine-131 in the dissolver off-gas stream to the total iodine contained in the dissolver. The earliest attempts to measure the release fraction involved calculating the amount of iodine in the fuel in the dissolver, and then measuring the amount of off-gas iodine-131. The method of measurement consisted of a stack air sample drawn from the 50-foot elevation of the stack. The sample was bubbled through a sodium carbonate solution and the radioactivity of the solution was



T Plant Av. 4.22, Std. Dev. 2.43, 144 Points
B Plant Av. 2.81, Std. Dev. 1.5, 196 Points
Both Plants Av. 3.41

FIGURE 4.4. Time Lag Between Dissolving and Extraction

measured with an ionization chamber in the middle of a coil of tubing containing the sodium carbonate solution. The chamber current (amperes) was then converted to curies of iodine-131. A knowledge of the stack air-flow and sample-line flow allowed an inference about the amount of iodine-131 going out the stack during dissolution. The integrated amount of "measured" iodine was then compared to the calculated amount in the dissolver. As experience with the measurement technique was gained, estimates of the release factor were revised, generally upward.

Iodine leaving the dissolver was modeled by using three release fractions:

RF_1 = the fraction of dissolver iodine sent out the off-gas line

RF_2 = the fraction of dissolver iodine in stack condensate

RF_3 = the fraction of dissolver iodine that was emitted during processing steps after dissolution via the building ventilation system.

Using these three fractions, the effective stack release fraction is given by:

$$RF_{EFF} = RF_1 - RF_2 + RF_3$$

In modeling the timing of the release, the delay in the iodine coming from post-dissolution processing (RF_3) was taken into account. It was assumed that on average, one day would be spent in the storage tank after dissolving (no emission), and that the balance left after 1 day's decay would be released over a 4-day period, corrected each day for decay (Acken and Bird 1945).

The stack condensate (RF_2) returns to the high-level waste collection system. This fraction reflects the degree of condensation that occurred inside the 291 stack. There was a collection pan at the bottom and a return line to plant high-level waste storage. Therefore, this fraction is subtracted from the other release fractions in calculating the effective release factor.

The Hanford documents relating to the iodine release fraction were examined to select the release fraction. Seventeen are summarized in Appendix B. Those having some information on the three release factors required in modeling iodine-131 releases are summarized in Table 4.4. References evaluated as "unsupported statement" may be based on undocumented experimental measurements, or may refer to one or more of the sources cited above, but do not contain measurement results. The average of twelve references with values of RF_1 is 0.82.

TABLE 4.4. Evaluated Release Factor Reference Summary

Ref	Date	Min	RF_1 Mid	Max	RF_2 Stack	RF_3 Disol	Basis
4	8/45		0.80				Lab results to Plant
5	12/45		0.72				7 cut stack gas measure
6	4/46		0.85		0.05		Unsupported statement
7	5/46				0 in summer		Unsupported statement
8	5/46		0.90				Unsupported statement
9	12/46		0.71				Unsupported statement
10	12/46		0.85		0.05		Unsupported statement
11	2/47		0.85				3 cut stack gas measure
12	7/48		0.85			0.05	Unsupported statement
13	6/51					0.10	Unsupported statement
14	1/52		0.80				Unsupported statement
15	7/52	0.80	0.86	0.92		0.05	Dissolver solution measure 6 cuts--range shown is 2 standard deviations. Post dissolution estimate refers to data in a reference that has been destroyed.
16	7/52		0.85				7 cut solution measure
17	4/55		0.85			0.10	Unsupported statement

73.74 Note: The *reference (REF) numbers refer to those listed in Appendix B.*

References 15 and 16 (Kirkendall 1952a and 1952b), however, are based on an inherently more accurate analytical procedure not available until the 1950s: measuring the remaining iodine in the dissolver after the completion of the cut. In determining the effect of air sparging, which was the motivation for the measurements, the best available technique was used. The cuts measured in these two references were meant to serve as "controls" on the air-sparged cuts. Hence, they were representative of the standard process that was used since the startup of T Plant in December 1944. They therefore may be applied to the 1944-through-1947 time period.

The stack sampling measurements, in contrast, were inherently less accurate. The current from the ionization chamber was typically read at 15-minute intervals, then integrated over the duration of the cut. The results were then converted to curies of iodine. During the measurement, the flow of sodium carbonate solution was held constant, the stack gas sample line flow was held as constant as possible, as was the stack gas flow. Everything depended on the relative flow of stack-to-sample line. Then the "measured" result was divided by a calculated iodine-131 inventory in the dissolver. In most cases this calculation is not given explicitly, leaving the degree to which the power history of the fuel being dissolved and properly accounted for unknown. There were also difficulties with retention of iodine on the internal surface of the sample line, as well as the difficulty in controlling background contamination in the 292 sample building itself.

In view of the greater accuracy expected with the dissolver solution residual iodine measurements of RF_1, in these references, it was decided to use the mean of the thirteen measurements from Kirkendall (1952a, 1952b), or 0.86.

For RF_2, the fraction of condensate collected at the stack bottom, two unsupported estimates in Apple (1946) and Work (1946) were used. One states that it was zero in the summer and the other states that it was 5%. A rounded average of 0.03 was selected for this release factor.

In the case of RF_3, the balance-of-processing factor, there were two unsupported estimates of 0.05, and two unsupported estimates of 0.10. Accordingly, an average of 0.075 was chosen.

With these choices, the effective release factor, RF_{eff}, is 0.86 - 0.03 + 0.075 = 0.905.

The STRM distribution functions relating to the releases are RFAC, which expresses the uncertainty in RF_1 - RF_2, the net stack release, and RESIDUAL, which expresses the uncertainty in RF_3, the fraction released after the dissolving step.

4.4 RFAC

Table 4.4, reference 15, gives a standard deviation around the 0.86 average of 0.03 based on six measurements. A piece-wise uniform distribution approximating a normal distribution centered on 0.83 with one-sixth of its area between 0.77 and 0.80, two-thirds between 0.80 and 0.86, and the remaining one-sixth between 0.86 and 0.89 was used. The normal distribution was chosen because it is well suited to represent true measurement error. The piece-wise uniform approximation was selected rather than an analytic representation because it has a fixed range and avoids the problem of returning low probability extreme values.

4.5 RESIDUAL

74 The nominal value of 0.075 was chosen because it is the average of 0.05 and 0.10 each from two reference sources (Table 4.4 references 12, 13, 15, and 17). Since there is no other information about how the release fraction might be distributed between these values, a uniform distribution between 0.*05* and 0.*10* was chosen.

STRM results for T Plant and B Plant dissolver cut iodine-131 content and releases are shown in Figures 4.5 through 4.8. All of these figures show the cut releases with plus or minus one standard deviation range. The 1944-through-1947 timeframe is covered and a more detailed look is taken at 1945 for each plant. Tables 7.1 and 7.2 in Volume II list the numerical results. Mean values, standard deviations, and the coefficient of variation (standard deviation divided by mean value) are given for 100 Monte Carlo realizations of this source term. The uncertainties range from 12% to 22% depending on the

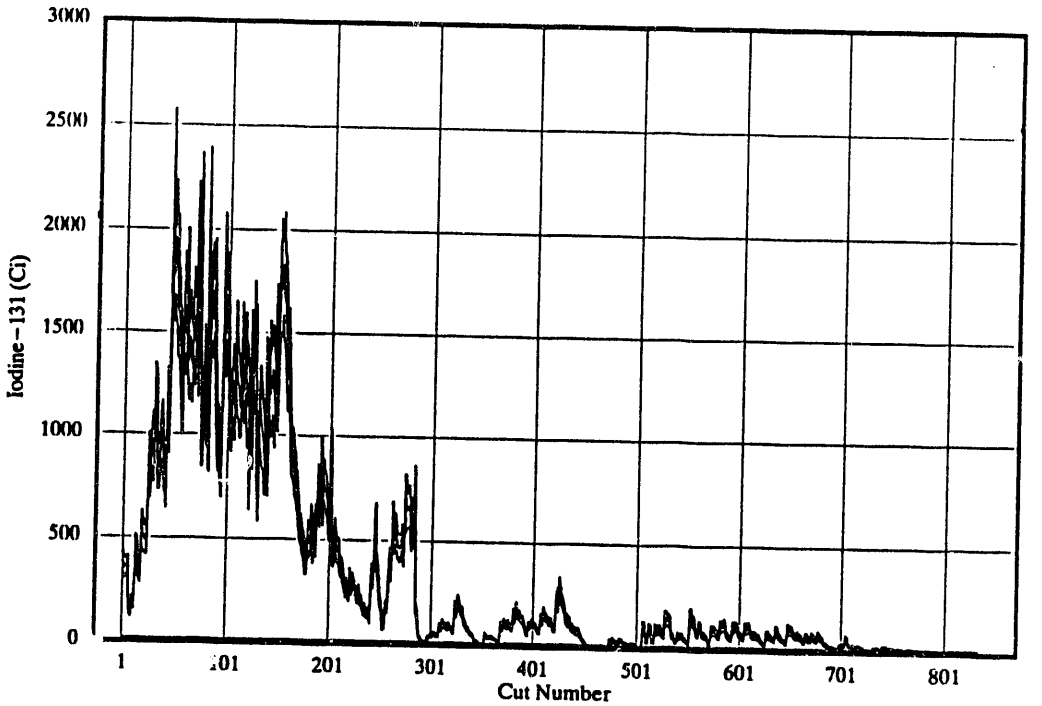


FIGURE 4.5. 1944 Through 1947 T Plant Cut Releases

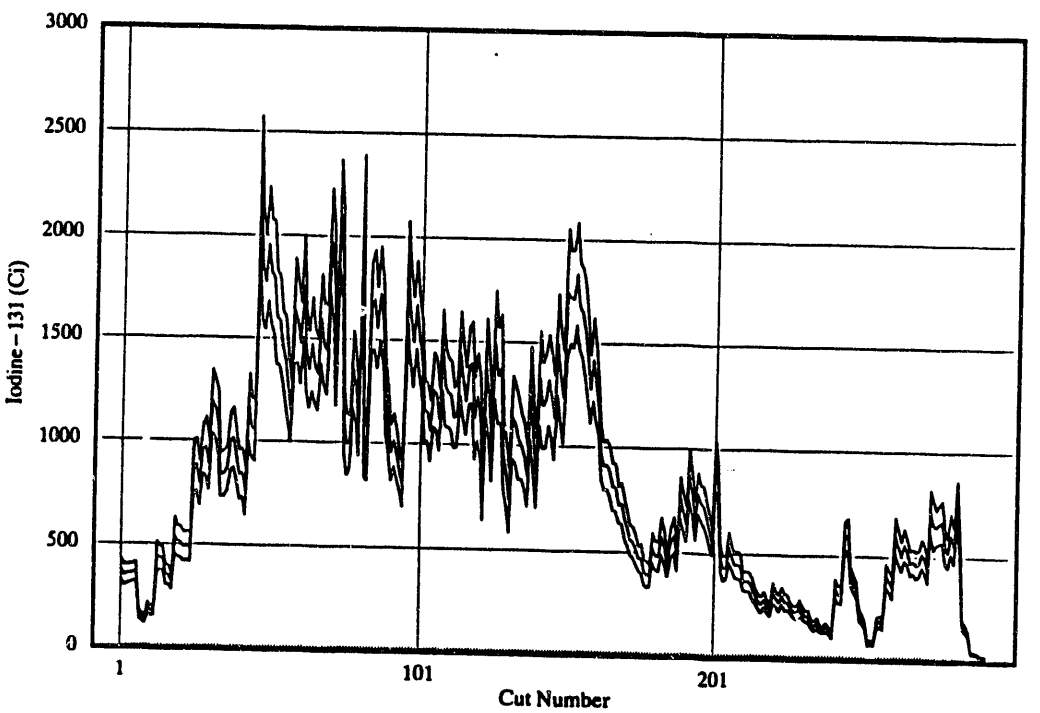


FIGURE 4.6. 1945 T Plant Cut Releases

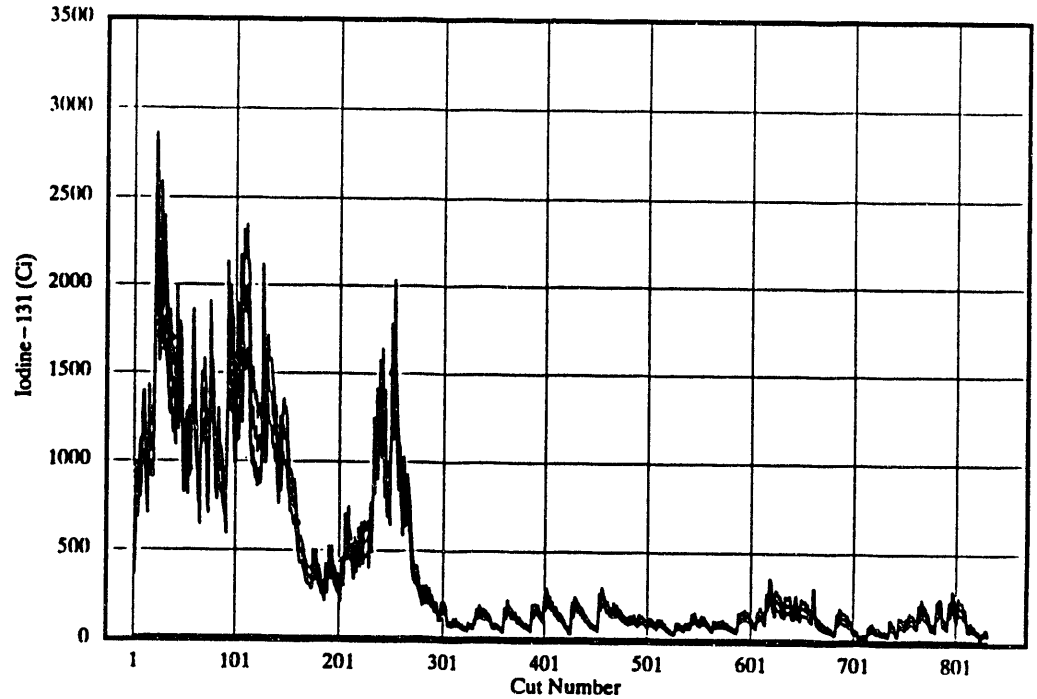


FIGURE 4.7. 1944 Through 1947 B Plant Cut Releases

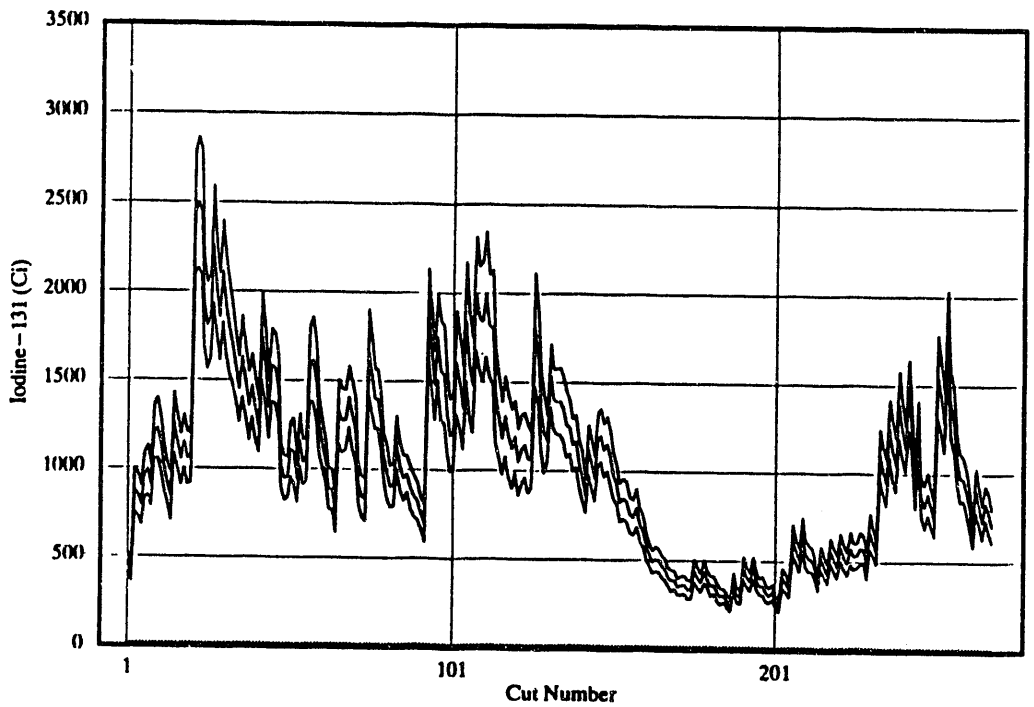


FIGURE 4.8. 1945 B Plant Cut Releases

reference source uncertainty distributions in effect. The ratio of released to dissolved iodine-131 is the effective release factor for the cut. This will center around 0.83 with some variation due to independent sampling. The releases thus do not include the iodine-131 released in processing steps after dissolving. These are included in the time-dependent releases in the next section.

For STRM cut releases the uncertainties associated with the magnitude and fraction of iodine-131 released in each cut resulted in standard deviations ranging from 12% to 20%. For daily releases the uncertainty in the release timing is introduced as well as releases from the post-dissolution processing steps. This adds considerably to the total uncertainty. The daily, monthly, and yearly summations are based on the hourly release estimates made by STRM. All modeled sources of uncertainty are present in these estimates. The daily numbers, therefore, reflect large uncertainty, ranging from 50% to factors of 2. The range in each of the hour estimates over the 100 realizations would be even larger. But when the daily estimates are aggregated into monthly estimates the ranges decrease from 6 to 10%, except for a few months with few cuts dissolved. The yearly uncertainties are in the 5% range.

The daily release estimates and their one standard deviation ranges are presented in Figures 4.9 through 4.13. A special figure is provided for 1945 to provide more detail for this largest release period. Table B.3 presents the daily values. Figures 4.14, 4.15, and 4.16 present the monthly releases for T Plant, B Plant and the sum for both plants. Monthly releases for both T and B Plants are given in Table 4.5.

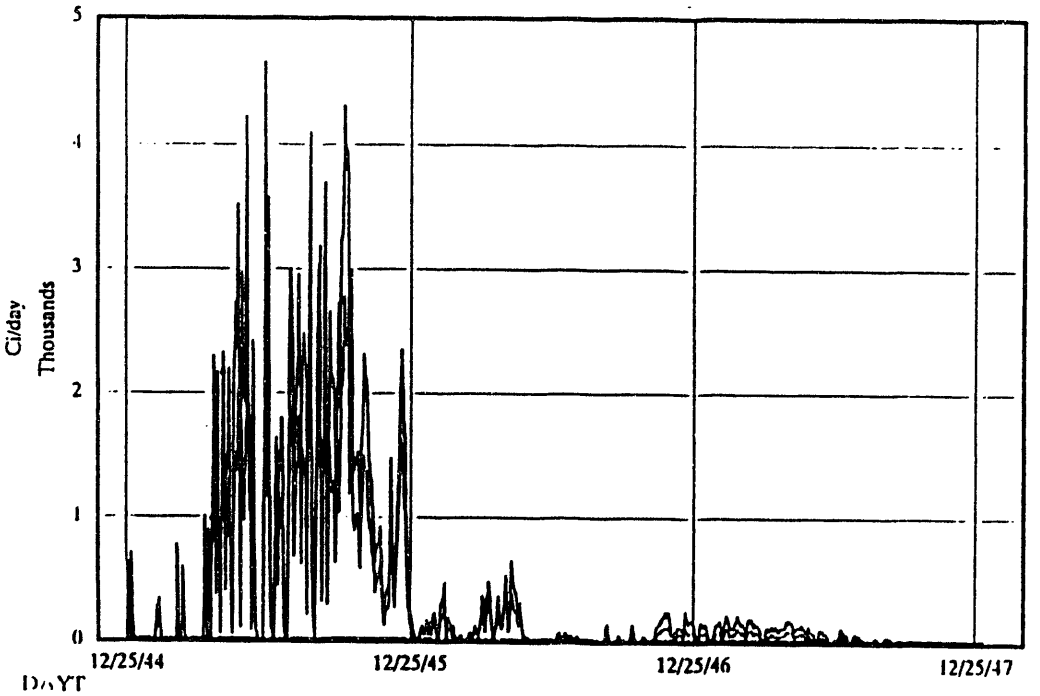


FIGURE 4.9. 1944 Through 1947 T Plant Daily Iodine-131 Releases

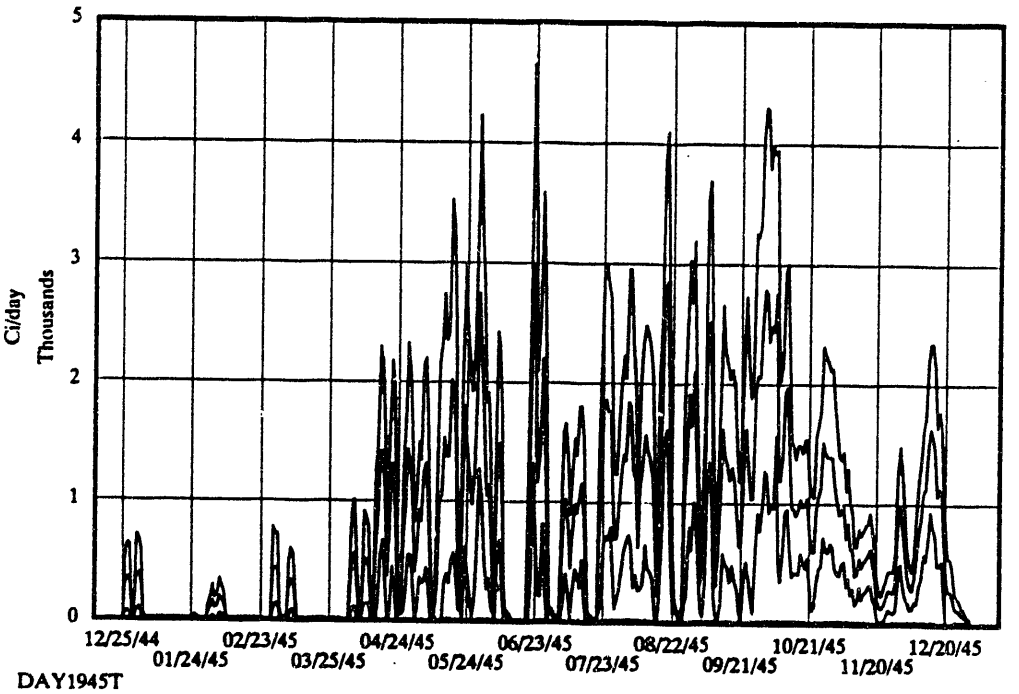


FIGURE 4.10. 1945 T Plant Daily Iodine-131 Releases

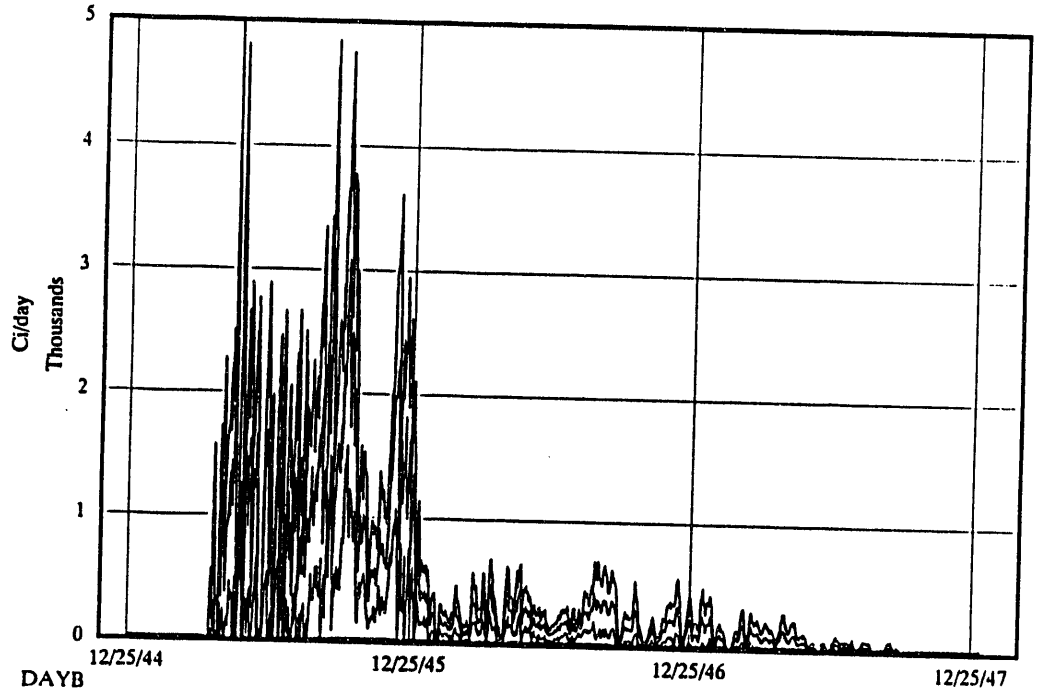


FIGURE 4.11. 1944 Through 1947 B Plant Daily Iodine-131 Releases

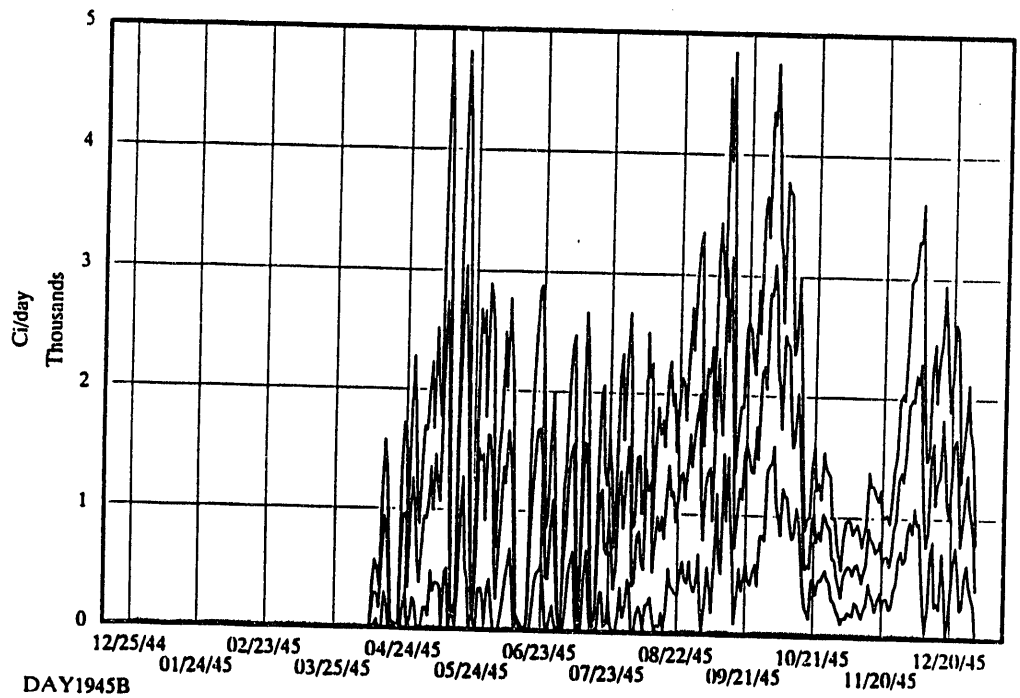


FIGURE 4.12. 1945 B Plant Daily Iodine-131 Releases

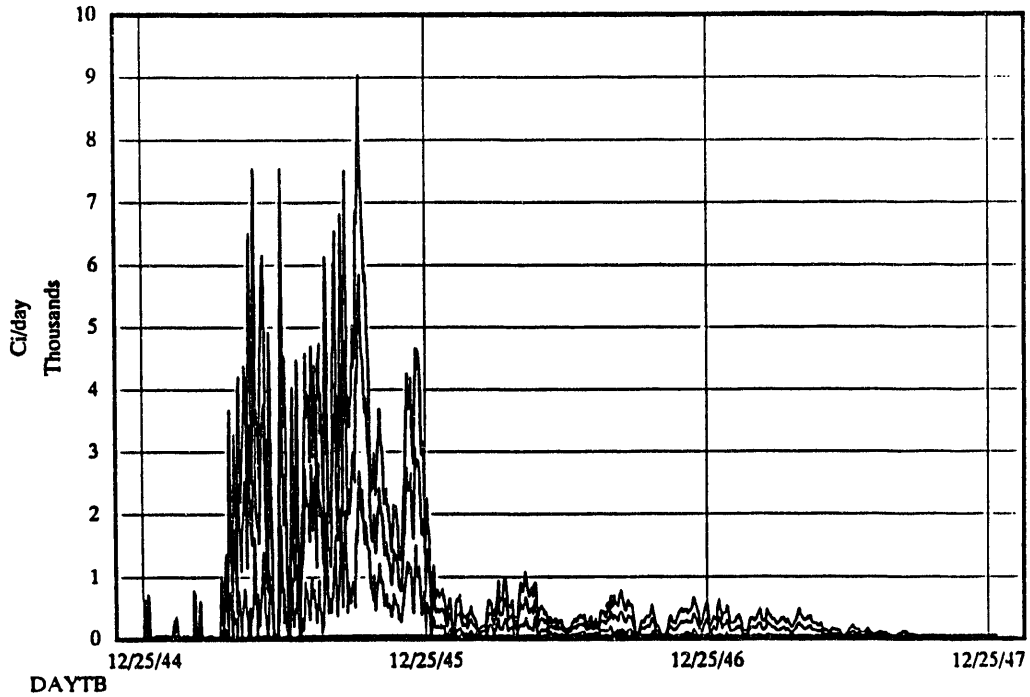


FIGURE 4.13. 1944 Through 1947 T and B Plant Daily Iodine-131 Releases

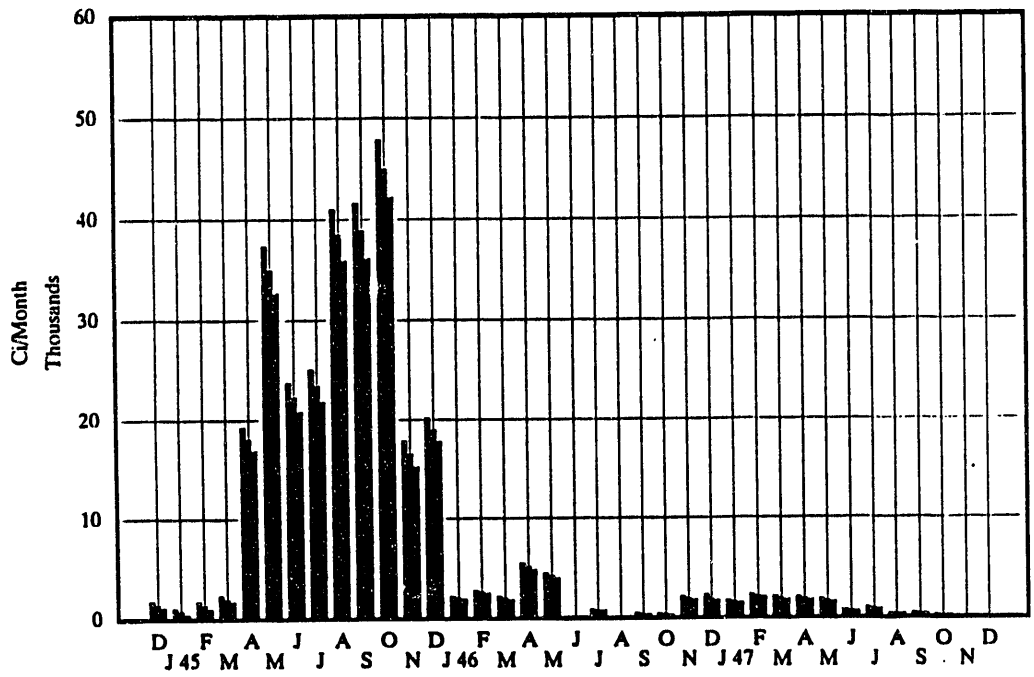


FIGURE 4.14. 1944 Through 1947 T Plant Monthly Iodine-131 Releases

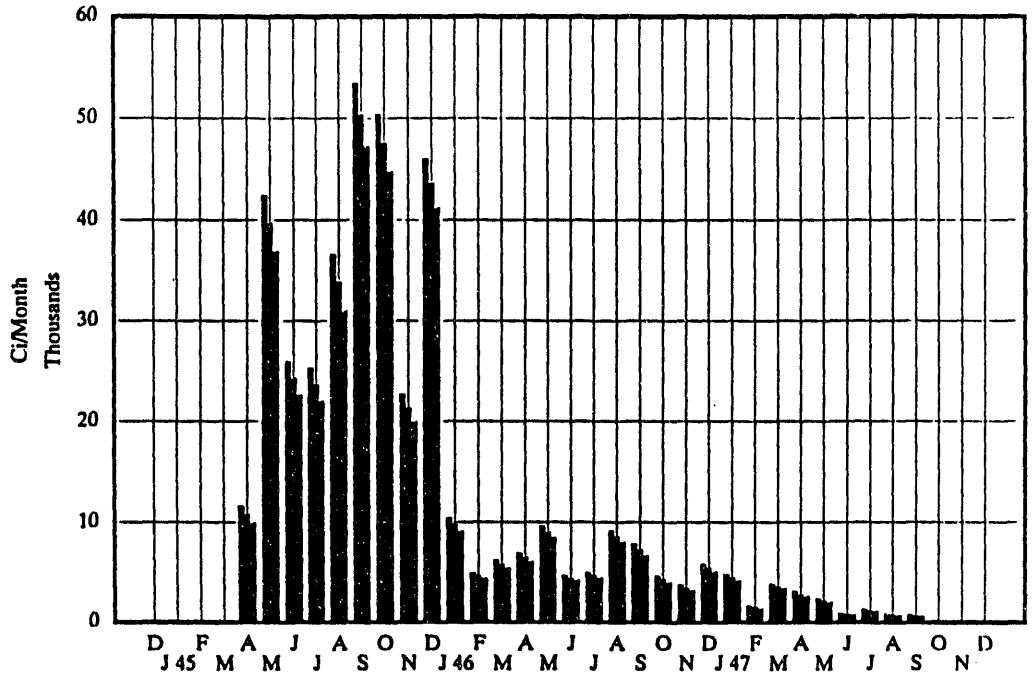


FIGURE 4.15. 1944 Through 1947 B Plant Monthly Iodine-131 Releases

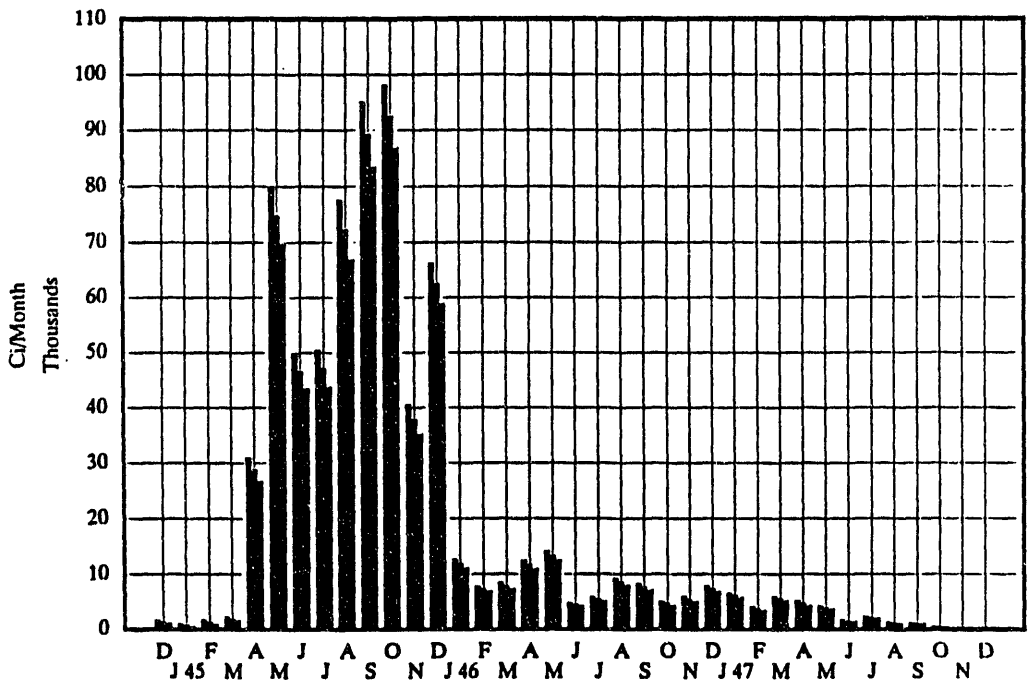


FIGURE 4.16. 1944 Through 1947 T and B Plant Monthly Iodine-131 Releases

TABLE 4.5. Monthly Releases of Iodine-131 from 100 STRM "Realizations"

61

Month	T Plant *I-131 Released (Ci)* Mean	T Plant Standard Deviation	T Plant Coefficient of Variation	B Plant *I-131 Released (Ci)* Mean	B Plant Standard Deviation	B Plant Coefficient of Variation
December	2,139	465	0.218			
January	1,221	435	0.357			
February	2,126	391	0.184			
March	2,082	320	0.154			
April	18,024	1,160	0.064	10,723	789	0.082
May	34,947	2,271	0.065	39,535	2,734	0.069
June	22,234	1,422	0.064	24,232	1,692	0.070
July	23,411	1,629	0.070	23,624	1,659	0.070
August	38,379	2,484	0.065	33,710	2,786	0.083
September	38,661	2,655	0.069	50,021	3,037	0.061
October	44,806	2,863	0.064	47,260	2,759	0.058
November	16,451	1,279	0.078	21,310	1,366	0.064
December	19,059	1,140	0.060	43,281	2,381	0.055
January	2,119	131	0.062	9,634	618	0.064
February	2,681	159	0.059	4,719	285	0.060
March	2,091	159	0.076	5,862	387	0.066
April	5,183	323	0.062	6,497	426	0.066
May	4,311	250	0.058	8,969	542	0.060
June	156	11	0.072	4,462	267	0.060
July	874	60	0.069	4,682	284	0.061
August	84	30	0.357	8,562	524	0.061
September	473	49	0.103	7,197	5443	0.075
October	439	58	0.131	4,381	327	0.075
November	2,062	151	0.073	3,463	297	0.086
December	1,961	142	0.073	5,436	363	0.067
January	1,671	141	0.084	4,487	326	0.073
February	2,256	165	0.073	1,579	161	0.102
March	1,980	164	0.083	3,637	244	0.067
April	2,006	175	0.087	2,847	276	0.097
May	1,785	158	0.088	2,203	167	0.076
June	780	81	0.104	873	86	0.099
July	1,039	74	0.071	1,257	86	0.068
August	464	47	0.102	790	68	0.086
September	480	44	0.091	279	50	0.069
October	307	28	0.090	183	16	0.086
November	157	14	0.090	120	11	0.093
December	176	11	0.063	102	9	0.088
Total	299,076			386,359		

5.0 CONCLUSIONS

75 The conclusions are described in both quantitative and qualitative comparisons to previous results *in* the following paragraphs.

5.1 QUANTITIVE COMPARISONS WITH PREVIOUS RESULTS

Anderson (1974) estimated that 340,000 Ci of iodine-131 were released from T and B Plants in 1945. The HEDR Phase I release estimate for 1945 was 317,000 Ci (Heeb and Morgan 1991). Using Anderson's release factor of 0.80 instead of the 0.75 figure used in Phase I, this would have been 338,000 Ci, close to his value. The current estimate is 560,000 Ci, an increase of 66%. What are the reasons for the large increase in the estimated releases?

The effective release factor has been increased from 0.75 (used in Phase I) to 0.905. That would account for only a factor of 1.21 of the 1945 increase. The Phase I calculation was based on Roberts (1957), which gave monthly average tons dissolved and an average cooling time. Table 5.1 lists the Roberts (1957) monthly tons processed and cooling time input data. Table 5.2 shows the comparable data averaged on a monthly basis from STRM output. A comparison shows that both dissolved approximately 2100 tons in the 3-year period. Figures 5.1, 5.2, and 5.3 show that there were some monthly discrepancies, but that the patterns were similar.

The average cooling time was shorter for the present reconstruction based on a mass-averaged cooling of every dissolver cut taken in time period; 59.6 days versus 61.7 for Roberts (1957). The difference of 2.1 days amounts to a factor of 1.20 more iodine-131. Figures 5.4 and 5.5 show that the pattern of monthly cooling times was similar with one or two large discrepancies, and that the HEDR times tend to be consistently lower in most of the months. The HEDR reconstruction is based on known individual reactor discharges and daily tonnages dissolved. The method of averaging monthly cooling times used in Roberts (1957) could not be determined (i.e, Were they mass-weighted?).

Another major difference comes from the use of discharge peaking factors (PF) from the Reactor Model. This was necessary because the iodine-131 concentration in spent fuel is proportional to the average power of the fuel

TABLE 5.1. Phase I Data from HWN-1991 (Roberts 1957)

Year	Month	T Plant Dischg Tons	T Plant Cooling Days	B Plant Dischg Tons	B Plant Cooling Days	T + B Plant Dischg Tons	T + B Plant Cooling Days
1944	December	9	49			9	49.0
1945	January	4	39			4	39.0
1945	February	7	53			7	53.0
1945	March	6	52			6	52.0
1945	April	20	41	13	44	33	42.2
1945	May	30	35	26	37	56	35.9
1945	June	17	33	17	37	34	35.0
1945	July	23	40	23	40	46	40.0
1945	August	26	39	33	39	59	39.0
1945	September	37	38	32	39	69	38.5
1945	October	55	44	63	44	118	44.0
1945	November	49	51	49	53	98	52.0
1945	December	51	53	46	41	97	47.3
1946	January	33	75	43	52	76	62.0
1946	February	28	70	45	65	73	66.9
1946	March	33	79	44	64	77	70.4
1946	April	46	62	46	61	92	61.5
1946	May	36	64	57	61	93	62.2
1946	June	30	87	52	65	82	73.0
1946	July	16	81	52	64	68	68.0
1946	August	10	86	68	60	78	63.3
1946	September	7	70	39	57	46	59.0
1946	October	7	69	50	64	57	64.6
1946	November	26	64	39	66	65	65.2
1946	December	19	67	36	60	55	62.4
1947	January	27	66	33	59	60	62.2
1947	February	20	64	26	72	46	68.5
1947	March	29	68	33	69	62	68.5
1947	April	29	69	33	68	62	68.5
1947	May	29	67	29	69	58	68.0
1947	June	14	72	30	79	44	76.8
1947	July	33	81	29	75	62	78.2
1947	August	23	85	29	79	52	81.7
1947	September	23	83	33	84	56	83.6
1947	October	21	87	20	94	41	90.4
1947	November	29	96	23	94	52	95.1
1947	December	29	96	27	94	56	95.0
	Sums	931.0		1218.0		2149.0	
	Average					61.7	

TABLE 5.2. HEDR Reconstructed Monthly Tons and Mass-Averaged Cooling Time

		T Plant		B Plant		T + B Plant	
Year	Month	Tons	Cooling Time	Tons	Cooling Time	Tons	Cooling Time
1944	December	3.6	32.7			3.6	32.7
1945	January	3.7	38.0			3.7	38.0
1945	February	6.9	53.1			6.9	53.1
1945	March	6.7	50.4			6.7	50.4
1945	April	23.2	43.9	12.2	42.4	35.3	43.4
1945	May	24.3	37.6	25.5	36.4	49.8	37.0
1945	June	15.8	36.7	18.2	36.8	33.9	36.7
1945	July	18.8	38.0	21.0	36.8	39.8	37.4
1945	August	31.8	37.4	29.5	35.9	61.2	36.7
1945	September	33.0	37.6	37.8	35.3	70.8	36.4
1945	October	54.3	40.4	62.2	41.6	116.5	41.0
1945	November	53.2	48.7	46.7	48.0	99.9	48.4
1945	December	48.4	53.0	44.5	37.6	92.9	45.7
1946	January	33.0	73.0	36.4	50.0	69.4	60.9
1946	February	25.1	65.8	47.5	62.7	72.6	63.8
1946	March	37.2	72.0	54.1	61.4	91.3	65.7
1946	April	43.9	58.3	42.3	57.5	86.2	57.9
1946	May	29.9	58.4	62.6	59.8	92.6	59.3
1946	June	18.0	92.2	46.2	63.9	64.2	71.8
1946	July	28.5	76.2	48.5	61.6	77.0	67.0
1946	August	12.1	82.0	60.5	57.4	72.5	61.5
1946	September	6.6	71.3	39.6	54.8	46.2	57.2
1946	October	6.6	69.5	47.4	62.2	54.0	63.1
1946	November	23.1	63.7	48.4	65.0	71.5	64.6
1946	December	22.7	65.1	37.4	58.1	60.1	60.8
1947	January	23.8	65.6	28.6	57.4	52.4	61.1
1947	February	23.1	61.3	24.2	69.2	47.3	65.3
1947	March	29.7	65.4	39.7	65.3	69.4	65.3
1947	April	26.4	65.9	29.7	65.6	56.1	65.7
1947	May	26.4	64.6	28.7	66.9	55.1	65.8
1947	June	15.4	71.5	30.8	75.6	46.2	74.2
1947	July	30.8	77.0	31.9	73.0	62.7	75.0
1947	August	25.3	82.2	26.4	76.5	51.7	79.3
1947	September	24.2	80.5	30.8	80.8	55.0	80.7
1947	October	23.1	84.7	23.1	92.1	46.2	88.4
1947	November	25.3	94.3	23.1	92.2	48.4	93.3
1947	December	26.4	99.6	23.1	98.1	49.5	98.9
	Sums	910.2		1208.3		2118.5	
	Average						59.6

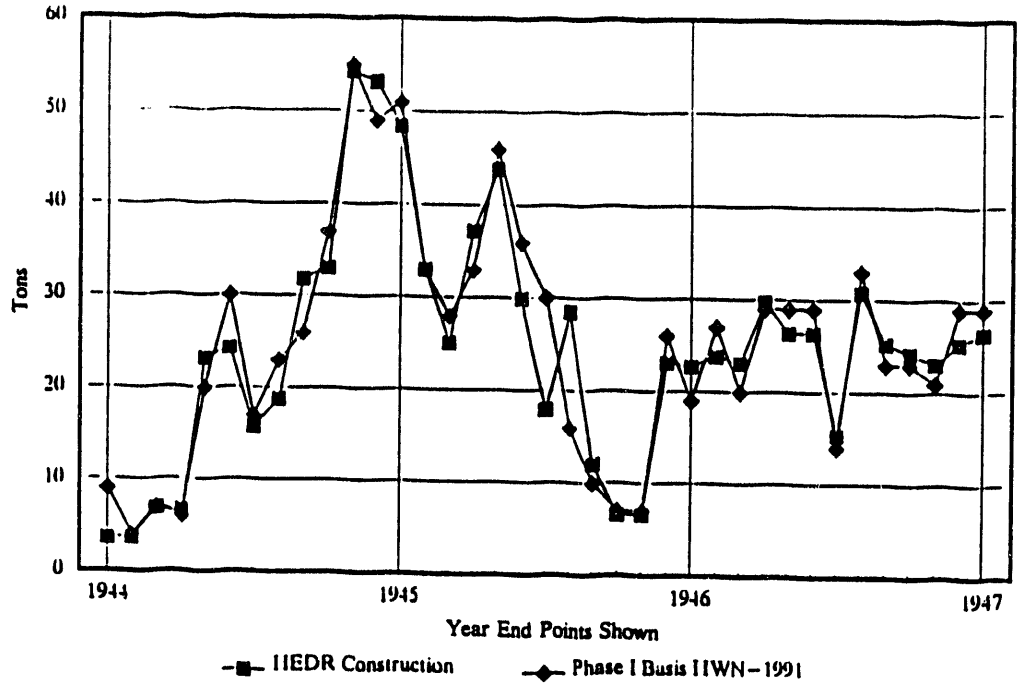


FIGURE 5.1. T Plant Tons Dissolved

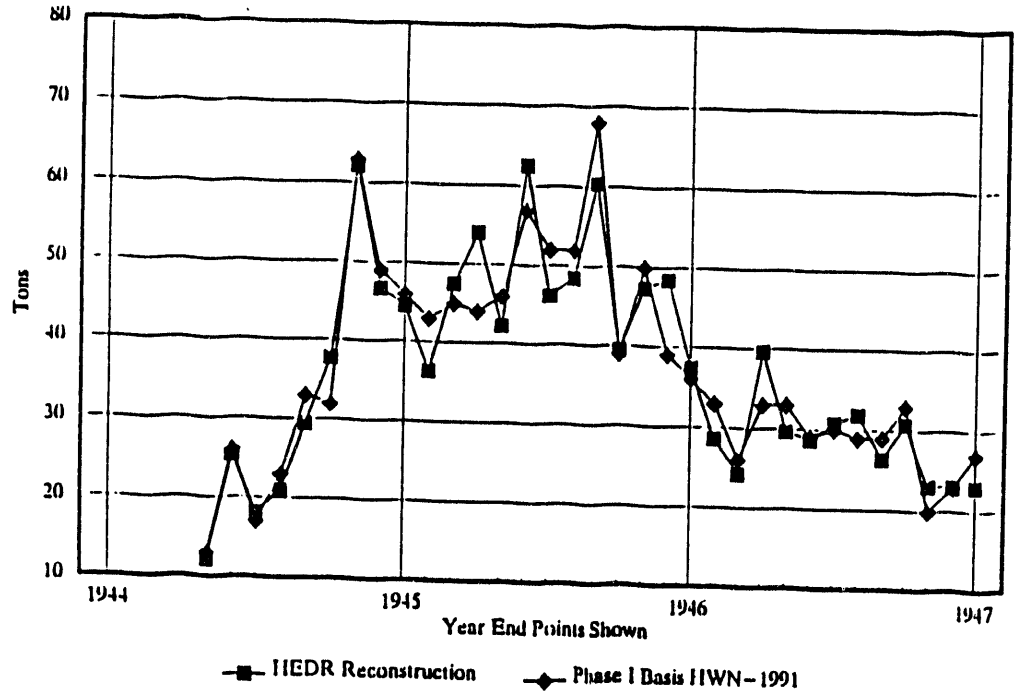


FIGURE 5.2. B Plant Tons Dissolved

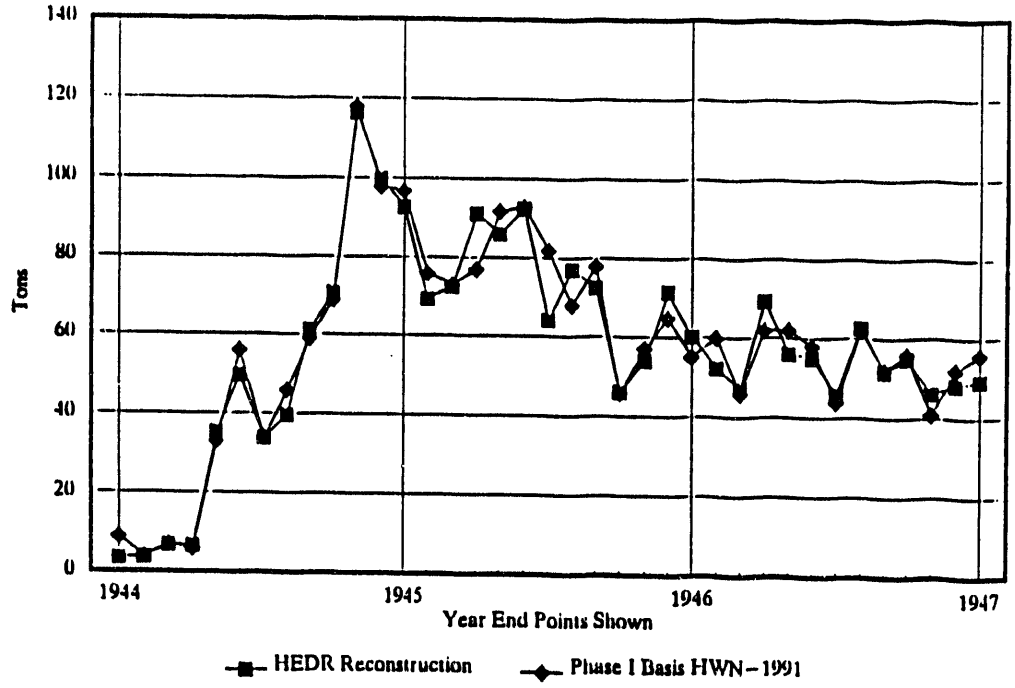


FIGURE 5.3. T and B Plant Tons Dissolved

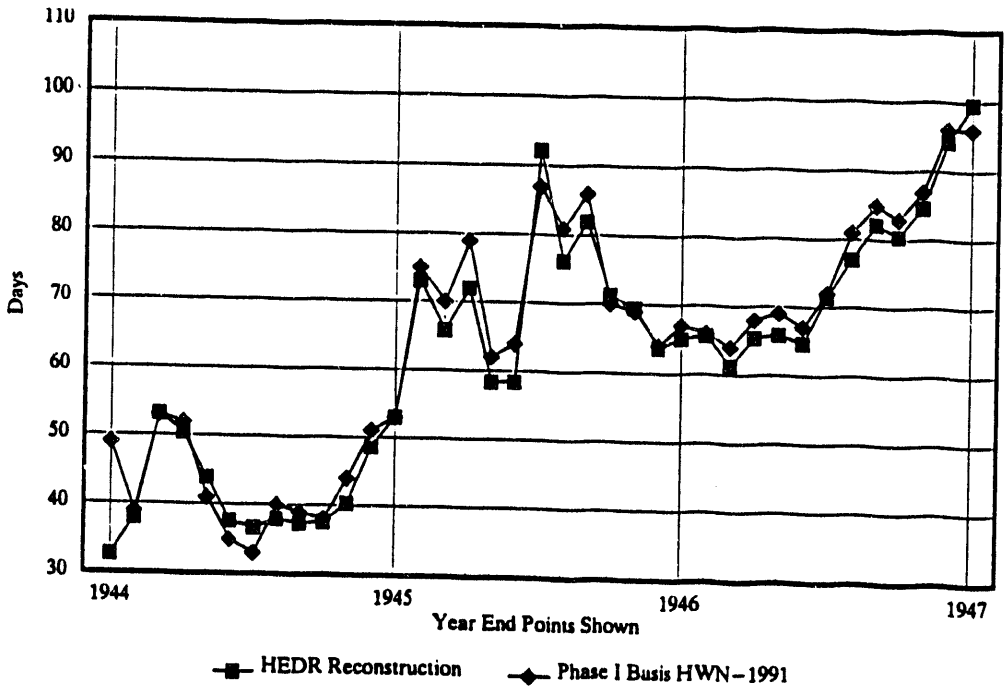


FIGURE 5.4. T Plant Cooling Times

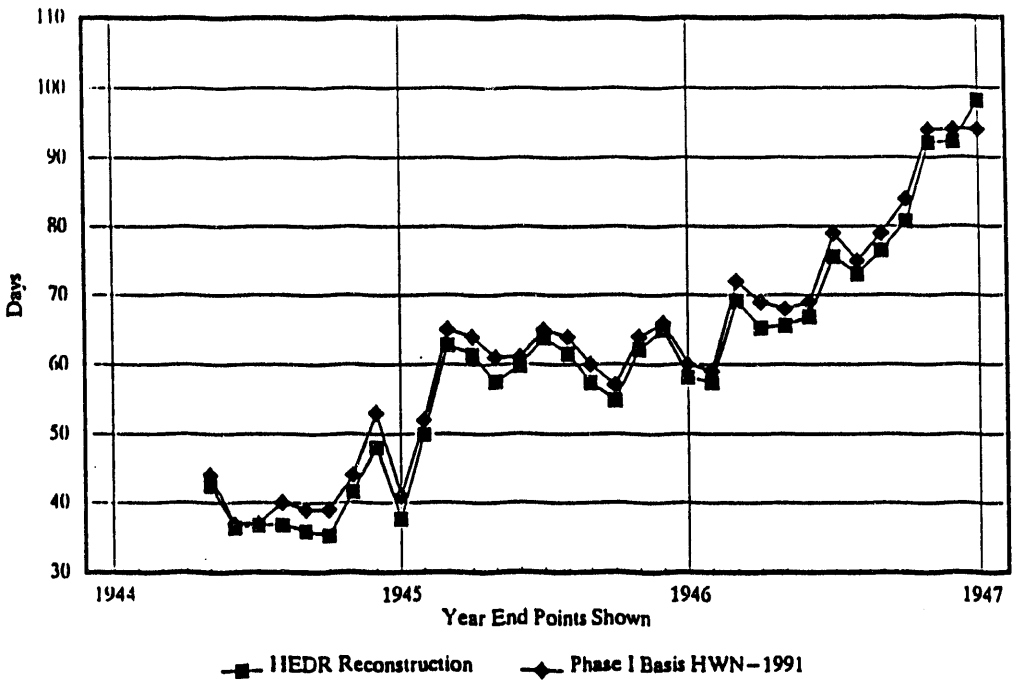
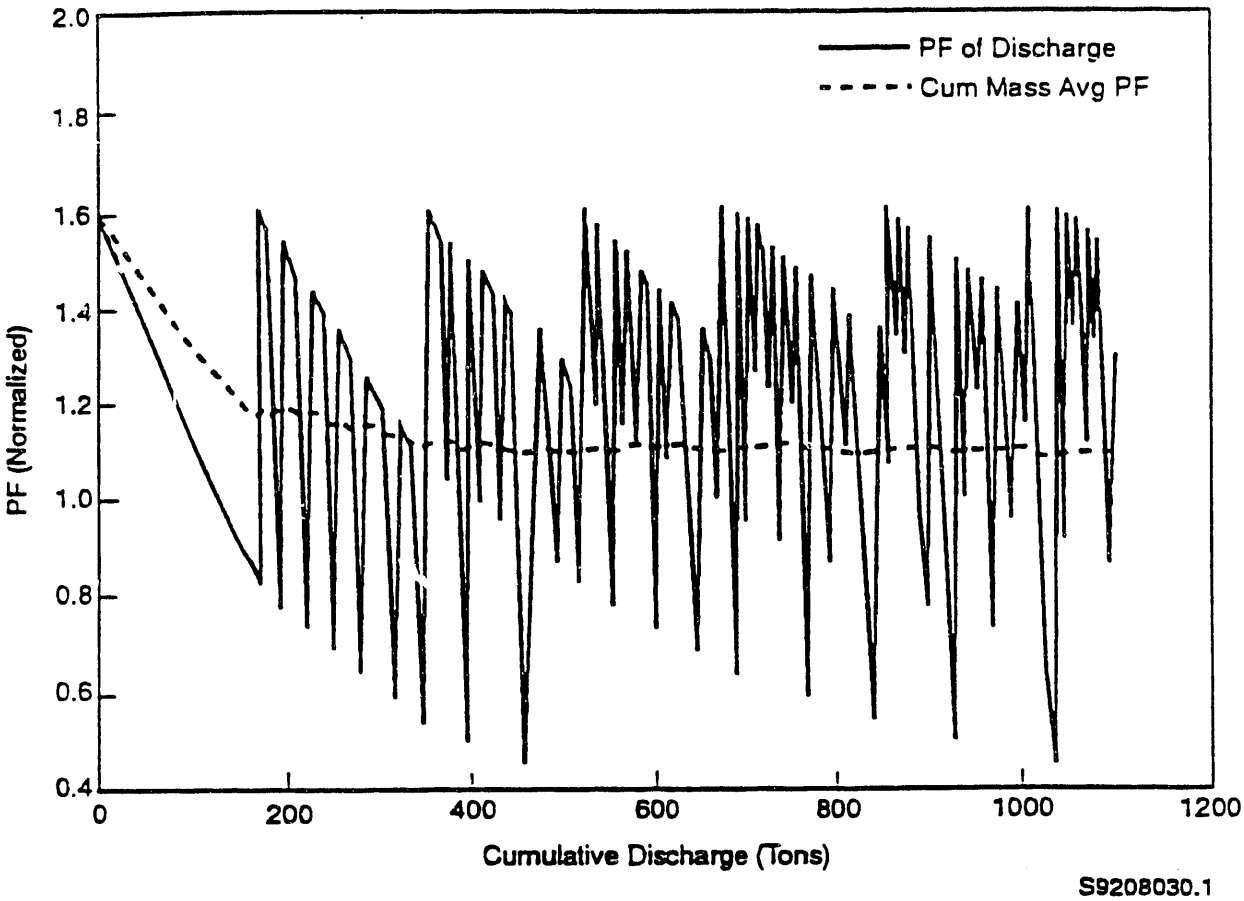


FIGURE 5.5. B Plant Cooling Times

76 in each discharge. This effect was not taken into account in the Phase I calculations or in the early estimates of the iodine-131 content. It is very important, especially when dealing with the earliest discharges from *a Hanford Production Reactor (HPR)*, to do this. The early discharges will come from higher-powered regions of the reactor because fuel in these regions will be the first to reach the goal discharge target exposure—200 MWd/ton in this early period. Figure 5.6 illustrates the situation. It shows the *PF* as a function of cumulative tons discharged from initial startup. The reactor power peak is assumed to be 1.6 (ratio of highest tube power to average tube power), which is typical for an HPR. The first fuel to reach 200 MWd/ton would have a *PF* of 1.6. The *PF* of first discharges will be much greater than unity. As the curve shows, however, the *PF* decreases until enough power has been generated in the higher-powered regions that they reach 200 MWd/ton for the second time and are discharged. Then the PF increases discontinuously up to the maximum again. These oscillations continue to be significant over the 3-year period covered. The cumulative mass averaged *PF* will eventually reach



PF is the Ratio of Average Power of Discharged Fuel to Average Power of Fuel In-Reactor

FIGURE 5.6. PF Power Factor of Discharge

1.10 as shown, but for most of 1945 it will tend to be much higher. The Reactor Model supplies a value for each discharge and realization.

77 For comparison purposes, a monthly calculation of dissolved iodine was done using the HEDR tons and cooling times. It assumed that the reactor was operated long enough to reach *a steady state* iodine-131 *concentration* of 24,174 Ci/ton (from Equation 4.2 with specific power P = 250MW/250 ton = 1 MW/ton) for each discharge. No *PF* was used:

$$\text{Monthly Dissolved Iodine-131} = 24200 \times \text{tons} \times e^{-0.0862 \times (\text{cooling time})}$$

This is compared to the HEDR Phase I results based on Roberts (1957) and with the HEDR reconstruction, which uses a *PF* and a more realistic iodine-131 concentration [does not assume saturation, but calculates a daily value based on the daily power history from the P-Department Reports (General Electric Company 1947)]. In practice, most of the discharges were within 10% of saturation, hence one would expect that differences between the HEDR reconstruction and the saturated calculation are largely due to the *PF*. The results are given in Table 5.3 and illustrated in Figures 5.7 and 5.8. During 1945, the HEDR reconstruction iodine remains significantly higher than the other two, and this is due to the *PF*. Figure 5.8 is plotted on a logarithmic scale to provide more resolution in 1946 and 1947. The total curies for the 3-year period are 626 kilocuries (KCi) for the saturated case, 762 KCi for the HEDR reconstruction, and 540 KCi for Phase I. The difference between the saturated case and Phase I is due mostly to the 2.1 day difference in cooling time. The ratio between HEDR and the saturated case (762/626 = 1.22) is due to the *PF*, which averages above its long-term 1.10 value by a factor of 1.22/1.10 = 1.11 because of the prevalence of initial discharges from the three reactors that were starting up for the first time during the period.

When the Phase I total release is compared to the HEDR reconstruction, for the 3-year and 1-month period, the increase is 685/*406* = *1.687*.

- The difference in cooling time of 2.1 days alone would be a factor of 1.20 ($e^{.0862 \times 2.1}$ = *1.198*).
- The difference from release fractions would be 1.21 (0.905/0.75 = *1.207*). The product *1.207* x *1.198* = *1.446* explains all but (*1.687/1.446* = *1.167*).
- The peaking factor average theoretically approaches a value of 1.10 (Figure 5.6). During 3 years of reactor startup and operation, an average value of *1.167* (the *PF* approaches the theoretical value from the high side) is entirely reasonable.

78 *Thus, the 1.687 increase consists of 1.198 from 2.1 days shorter cooling, 1.207 increased release factor and 1.167 PF: 1.198 x 1.207 x 1.167 = 1.687.*

TABLE 5.3. Comparison of Dissolved Iodine-131 as Calculated by the Saturated Case, the HEDR Reconstruction, and Phase I

Year	Month	Sat. Iodine, Ci	HEDR Recon. Iodine, Ci	Phase I Iodine, Ci
1944	December	5209	1298	2109
1945	January	3399	1269	1351
1945	February	1704	1181	1670
1945	March	2089	2762	2240
1945	April	20331	32189	27200
1945	May	49661	84352	76000
1945	June	34581	48814	39721
1945	July	38410	53040	34411
1945	August	62696	78604	48109
1945	September	74660	104066	58979
1945	October	81983	100709	62528
1945	November	37323	41982	26154
1945	December	54082	68763	44009
1946	January	30897	11981	12642
1946	February	7238	8450	5479
1946	March	8392	8901	5014
1946	April	14163	12728	10796
1946	May	13472	14603	10379
1946	June	4693	5184	4899
1946	July	6785	6105	5264
1946	August	10638	10056	9214
1946	September	8816	8395	7133
1946	October	5795	5408	5155
1946	November	6621	6449	5559
1946	December	8037	8441	6190
1947	January	6926	7137	6947
1947	February	4342	4257	3123
1947	March	6005	6610	3968
1947	April	4689	5503	3990
1947	May	4601	4540	3897
1947	June	1887	1887	1442
1947	July	2394	2572	1782
1947	August	1384	1464	1108
1947	September	1272	1345	979
1947	October	577	588	416
1947	November	377	318	337
1947	December	237	326	366
	Sums	626366	762277	540551

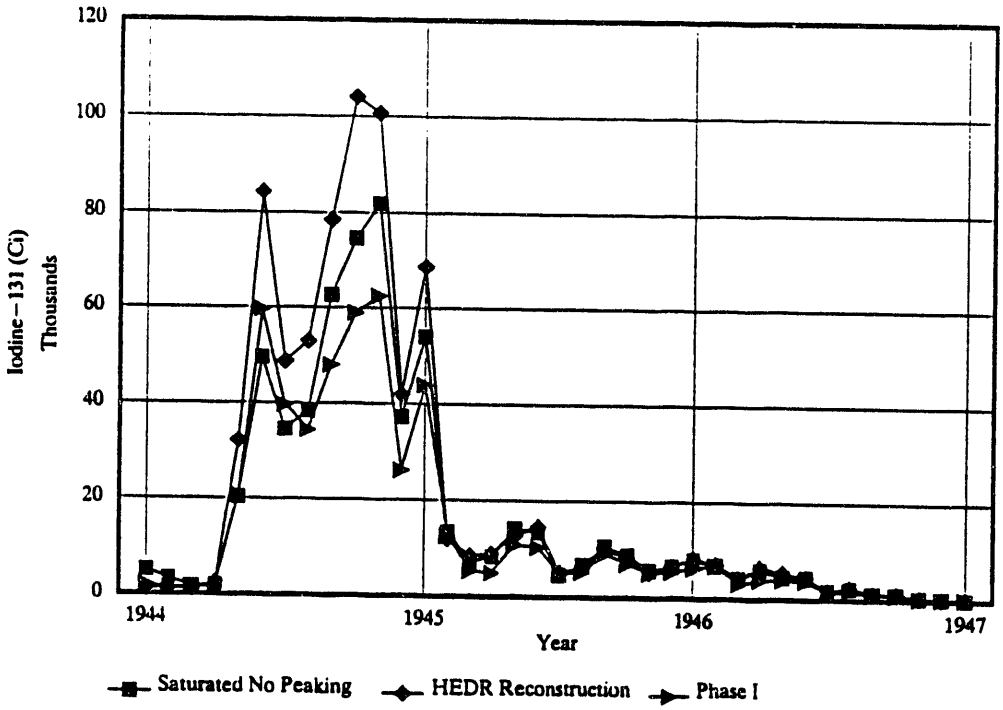


FIGURE 5.7. Dissolved Iodine-131, Linear

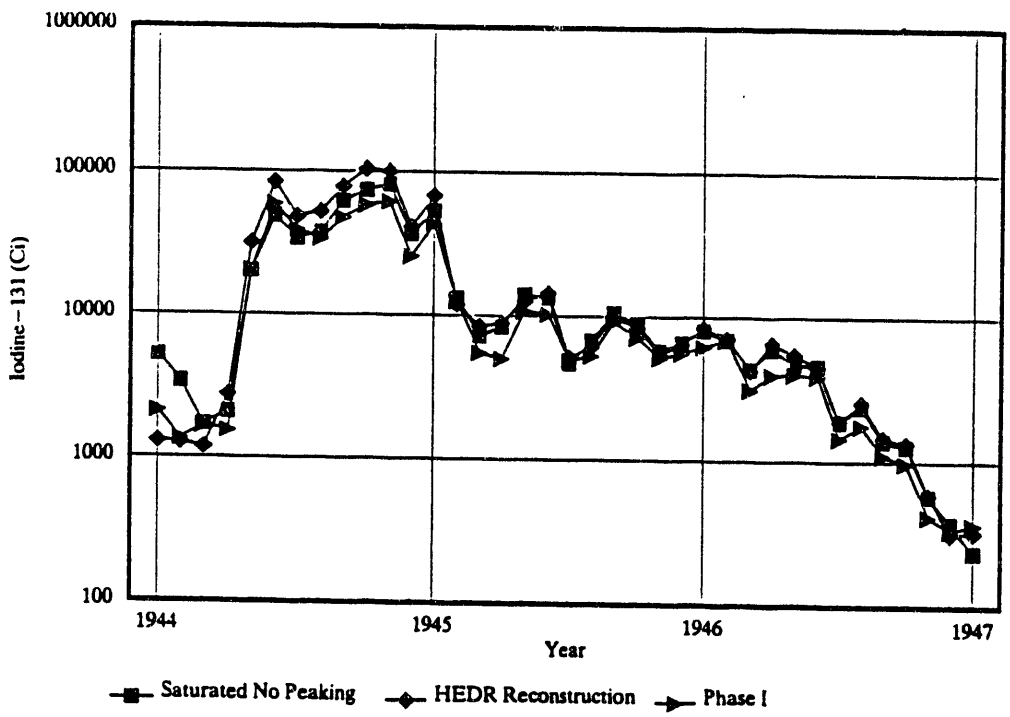


FIGURE 5.8. Dissolved Iodine-131, Log

5.2 QUALITATIVE COMPARISONS WITH PREVIOUS RESULTS

Both Anderson's (1974) original results and the Phase I results were based on monthly average values of tons processed and cooling time. The results were very similar. The question of finding records that would make it possible to present a much more detailed iodine-131 source term for dose calculations remained.

The P-Department Reports (General Electric Company 1947) afforded the possibility of forming a reliable, detailed estimate of iodine-131 creation at Hanford. On the separations side, there was less detailed information. The document search produced in April 1991, the 200 Area Reports (Acken and Bird 1945; Bird and Donihee 1945), the Metal History Reports (General Electric Company 1946), and Jaech (undated). These have made possible the present detailed reconstruction of the iodine-131 source term.

Each of these sources do not, in themselves, provide exact daily information. However, as a group, they do provide ample cross comparisons. The amounts and dates of reactor discharges from the P-Department Reports (General Electric Company 1947) agree almost exactly with the three separations references. Jaech (undated), with the few exceptions noted, agrees with the two daily sources. The agreement is not absolute, which indicates that Jaech (undated) represents an independent summation of the primary data sources.

The agreement is achieved over the range of 1929 dissolver cuts and 226 reactor pushes. Lindvig (1946) provided time-of-day information on 330 dissolver cuts.

The use of Monte Carlo techniques permits the definition of uncertainty ranges of the iodine-131 hourly releases which, with high probability, contain the actual hourly releases. Hourly iodine-131 releases were only known on the infrequent occasions when they were measured. The hourly release ranges calculated by STRM are continuous for the whole 3-year period.

6.0 RECOMMENDATIONS

The release estimates are based on all of the pertinent records known. The method of reconstructing the iodine-131 releases uses statistical modeling techniques that take into account the areas where complete information was not found. It is, therefore, concluded that a sufficiently well-defined estimate of the iodine-131 releases has been obtained, and recommended that these estimates be used as input to the HEDR air transport model as the second step in determining the doses received by the public from Hanford Site iodine-131 releases in the 1944 through 1947 period.

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APPENDIX A

THE REACTOR MODEL

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THE REACTOR MODEL

A.1 INTRODUCTION

The reactor model (RM) chosen represents a Hanford Production Reactor as a one-dimensional cylindrical reactor. The solution to the one energy group neutron diffusion equation in this geometry is the Bessel function $J_0(2.405r/R)$, where r is the radius of a point in the core (fuel-containing region) and R is the outer physical radius of the core plus an additional "extrapolation" distance. R can be chosen so the calculated ratio of the maximum (at the center) to average power in the core matched the measured power peaking determined by the recorded ratio of the highest powered tubes to the average tube power.

This approximate model gives an idea of the population of tubes at a given power relative to the average power. The power distribution is computed on a daily basis in 244 fixed equal area annular regions. Figure A.1 shows the first 25 regions. An accounting of the exposure in each region is maintained. When a discharge is indicated by the P-Department Reports (General Electric Company 1947), fuel nearest the exposure goal is discharged from the model and replaced by fresh fuel. The peaking factor (ratio of residence-time average power to pile power for the same period) is calculated. This reconstructs the missing information that was not recorded and allows an estimate of the iodine content of the fuel. An iodine content is also calculated for each discharge using the daily reactor power history.

Four model uncertainties are sampled when the code is run in Monte Carlo mode:

- Daily Pile Power
- Daily Peaking Factor
- Tons Loaded
- Tons Discharged.

The code calculates peaking factor and iodine-131 concentration (Ci/ton) for each of the 226 discharges that were dissolved. It does this for 100 realizations which differ as a result of sampling the four parameters above from distributions which describe their uncertainty. This information is given to STRM via the PF file; see Figure 6.1.

The model is validated in terms of its ability to predict the exposure of each reactor discharge. Discharge exposure is included in the P-Department Reports (General Electric Company 1947). Figures A.2, A.3, and A.4 show the discharge exposures for the three reactors B, D, and F and the predicted exposure range from RM. In general, the computed and measured exposure matches fairly well. Of the 226 discharges, 92.5% have estimated exposures within 10% of the reported exposures and 99.9% have estimated exposures with 15% of the reported exposures. Maximum discrepancies are within the ±15% range.

A.2 THE PEAKING FACTOR ALGORITHM

1. The Hanford reactors can be represented by long horizontal cylinders that can be divided, for modeling purposes, into equal-volume concentric shell or rings as shown in Figure A.1. This cylindrical model represents the 2004 process tubes in the B, D, and F reactor core design. The dimensions of each "equivalent cell," which includes fuel, cladding, water annulus, process tube and surrounding graphite was 8.375 by 8.375 inches. The total area of the reactor face was therefore 976 square feet, and the radius of the equivalent cylinder was 17.6 feet.

2. If the pile power were constant with respect to radial position, each ring would have the same amount of power. For example, if we divided the cylinder into 25 equal-volume rings and on a given day the power was 250 megawatts, then each ring would generate at 10 megawatts. If each ring contained 10 tons of material, then the above exposure would be 1 megawatt-day/ton (MWd/ton) each day. If the process tubes were discharged after they reached 200 MWd/ton, then all the tubes would be ready for discharge after 200 days.

3. The power distribution in the pile is not flat. The peak tube powers generally were in the central 600 tubes in actual reactor operation. A good approximation to the radial flux variation is a J_o Bessel functi : which is computed as follows:

$$J_o = 1 - X^2/4 + X^4/64 - X^6/2304 \pm .....$$

where x = (2.405r/R), R is the extrapolation radius of the pile and r is the radius of the ring. In general, this will be well into the reflector (the region surrounding the core beyond 17.6 feet).

4. Table A.1 lists the relative ring power based on a Bessel function with a 1.6 peak power at the center of the 25 ring example discussed in Step 2 above. During most of the 1944-through-1947 period the power peak was near 1.6.

   Since the process tubes in the first ring are pushed every 130 days, these tubes will be pushed three times as often as fuel in the last ring, which is discharged every 383 days.

   Because the higher power process tubes are pushed more frequently, the average relative power in the discharges will be greater than 1 in the long run. For this example, the long run average relative power is 1.095. Although the reactor model in Figure A.1 operated at an average power density of 1 megawatt per ton of fuel, the average power density of discharged fuel would be 1.095 megawatts per ton.

5. The maximum tube power is calculated as follows:

$$\text{Max. tube power(kw)} = 0.2635 \text{ kw/°C/GPM} \; * \text{tube flow (GPM)} * \Delta T_{max}(°C)$$

   where tube flow = nominal central zone tube flow = 20.0 GPM

   ΔT_{max} = maximum tube outlet water temperature - inlet water temperature (°C)

   0.2635 = conversion factor to kilowatts.

A.3 MODEL OPERATION

The actual average discharge exposures varied significantly around the 200 MWd/ton goal as shown in Figures A.2, A.3, and A.4. According to P-Department Reports (General Electric Company 1947), the over 300 MWd/ton discharges were actually a combination of 200 MWd/ton and 400 MWd/ton discharges. To achieve a 400 megawatt/ton discharge one of two things had to happen: the fuel was left in-pile twice as long or the reactor power was peaked. The first explanation applied well to B and D reactors, which operated long enough for the fuel in some process tubes to reach 400 MWd/ton using the peaking factors derived from the

TABLE A.1. 25 Ring Model Power and Residence Time

250 MW Pile Power, 250 Tons Loaded,
Discharging at 200 MWd/ton

Ring	Relative Ring Power	Residence Time to reach 200 MWd/ton Days
1	1.547	130
2	1.495	134
3	1.444	139
4	1.394	145
5	1.345	149
6	1.297	155
7	1.249	161
8	1.202	167
9	1.156	174
10	1.111	181
11	1.067	188
12	1.023	196
13	0.980	205
14	0.938	214
15	0.897	223
16	0.856	234
17	0.816	246
18	0.777	258
19	0.739	271
20	0.701	286
21	0.664	302
22	0.628	319
23	0.592	338
24	0.557	360
25	0.523	383
	25.000	

daily maximum tube temperatures. F reactor is different—the 400 MWd/ton material could not be produced that quickly using the peaking factors derived from the daily operations information. Therefore, it had to be assumed that the reactor power was peaked, via control rods, to have a higher exposure in the center than indicated by the daily operations information.

For the model, the pile is divided into 244 rings (4 ft^2 each—976 ft^2 in total). For the B Reactor, not all of the rings were used in the

beginning. This reactor started out using only 1004 of the 2004 process tubes (123 rings). Then it moved to 1128 tubes (138 rings), 1300 tubes (159 rings), 1500 tubes (183 rings), 1595 tubes (195 rings), then finally 2004 tubes. The physics (the Bessel function) is based on the rings having equal volume. However, to simplify the computer algorithm, the Bessel function is applied to rings of equal weight; this assumes that the relationship between volume and weight is a constant.

84 The computer algorithm works on a daily time step. The peak power in the central region, p0, is calculated for the day from the daily operations information (with the exception of the early operations of the F Reactor, see above). If p0 cannot be calculated for a day due to missing data in the records, the previous p0 (for a 24-hour operating period) is used. Additionally, if p0 is greater than 2.28 or less than 1.0, then the previous p0 is used. The appropriate peaking factor for each ring for the given p0 is then determined. The Bessel function does not have to be recalculated each time. For each ring the peaking factor is *linearly proportional to p0.*

84 Once the peaking factor for each ring is determined, the power for that day is allocated to each of the equally weighted rings. Actually there are two allocations, once according to the peaking factor (where the central rings get more power than the outer rings according to *a normalized* Bessel function), called ring-power, and the second allocation of equal power to all rings, called pile-power. The daily process continues until it is time for a discharge. To calculate the iodine-131 in the pile, the sum of the previous power history is decayed one day, and the current power is then added to the sum (Equation 4.3, Section 4.0).

At discharge, the rings are sorted according to exposure in each ring. It is assumed that the rings with the largest exposure will be pushed first. However, this assumption is modified to allow a set of rings to remain in the reactors long enough to achieve 400 megawatts/ton. Additionally, it is clear from the megawatts/ton records (see figures) that early in the operations of the B and D Reactors, rings with less than the highest accumulated power were discharged. At

that time, the operators were learning how to operate these reactors, and process tubes were emptied and replaced with neutron-absorbing "poison columns," to flatten the reactor power distribution; the choice of what tubes to push were not based on the highest power at that time.

For the early operations of the reactors, in the computer algorithm, rings that were retained were determined the old fashioned way—the program was rerun with different choices until we got the best match with the known discharges. The tons pushed were from the daily operations record, along with the tons of material that were charged after the push. The peaking factor for a push is calculated by simply summing the ring-power in the rings pushed and dividing by the sum of the pile-power in the rings pushed. These sums are weighted by the tons pushed in each ring, since the tons in the push did not equal the tons in the rings—that is, only a portion of one ring would be pushed. The remaining portion would then be pushed at some future discharge. The computer algorithm thus has to reallocate the rings to continue to fuel mass and energy in the reactor.

CYLINDRICAL MODEL
RINGS OF EQUAL AREA

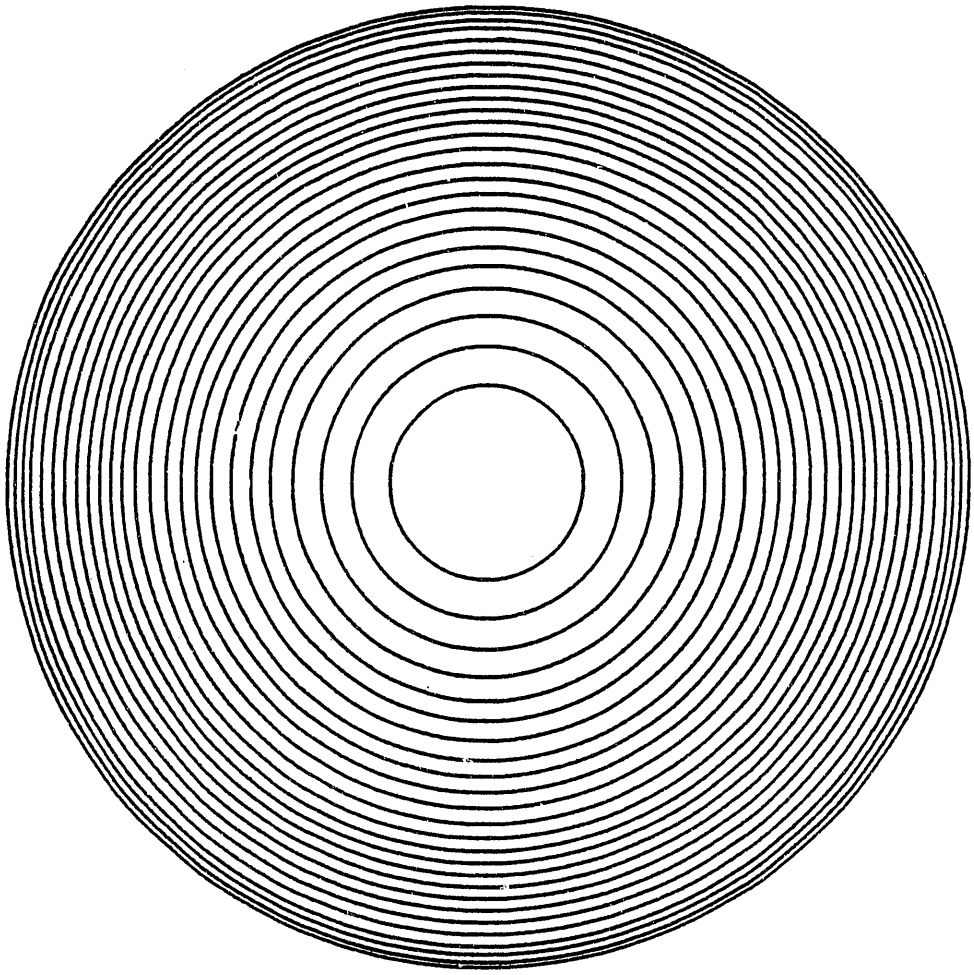

FIGURE A.1. Ring Model of Reactor

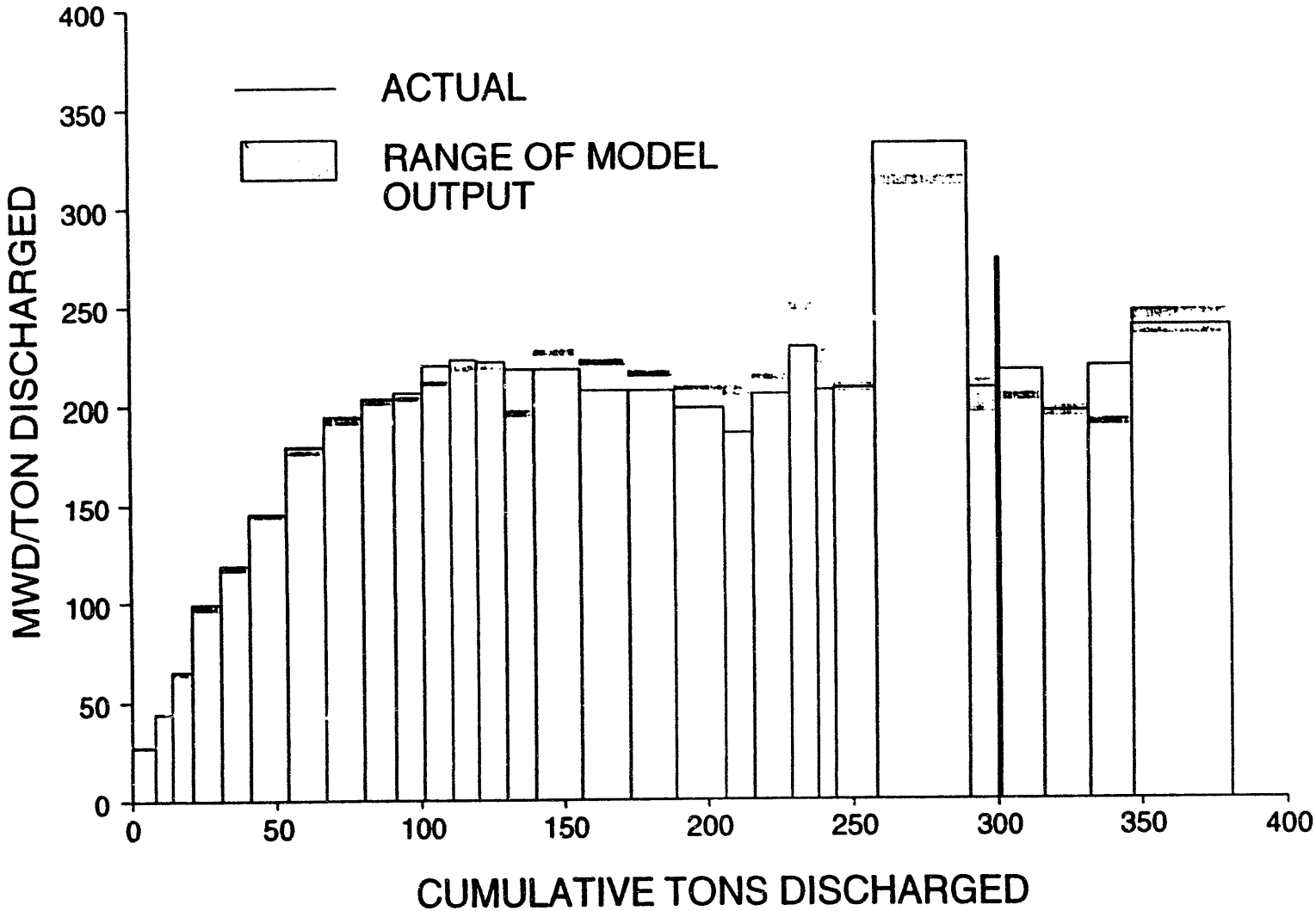

FIGURE A.2. Estimated Exposures of B Reactor Discharges

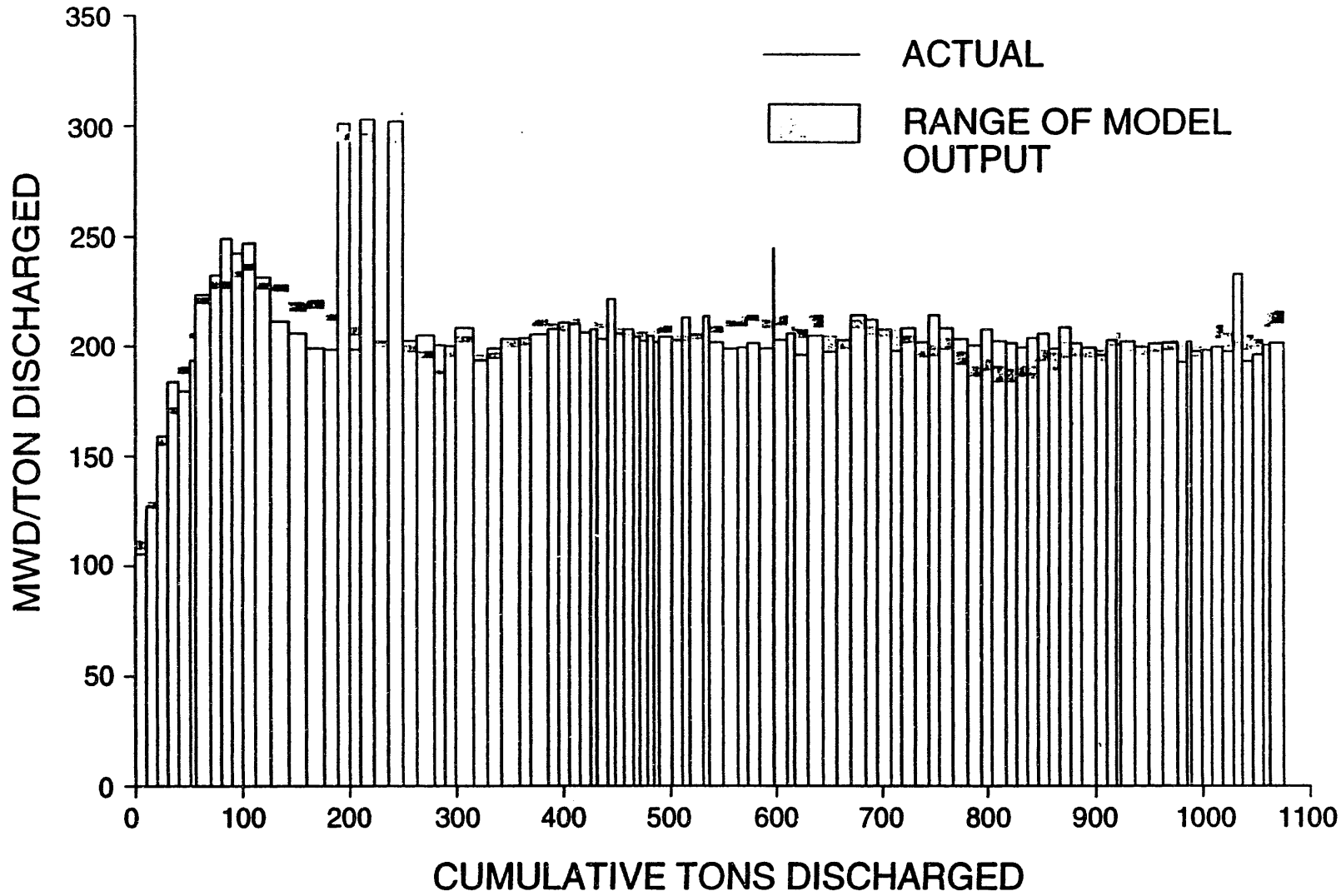

FIGURE A.3. Estimated Exposures of D Reactor Discharges

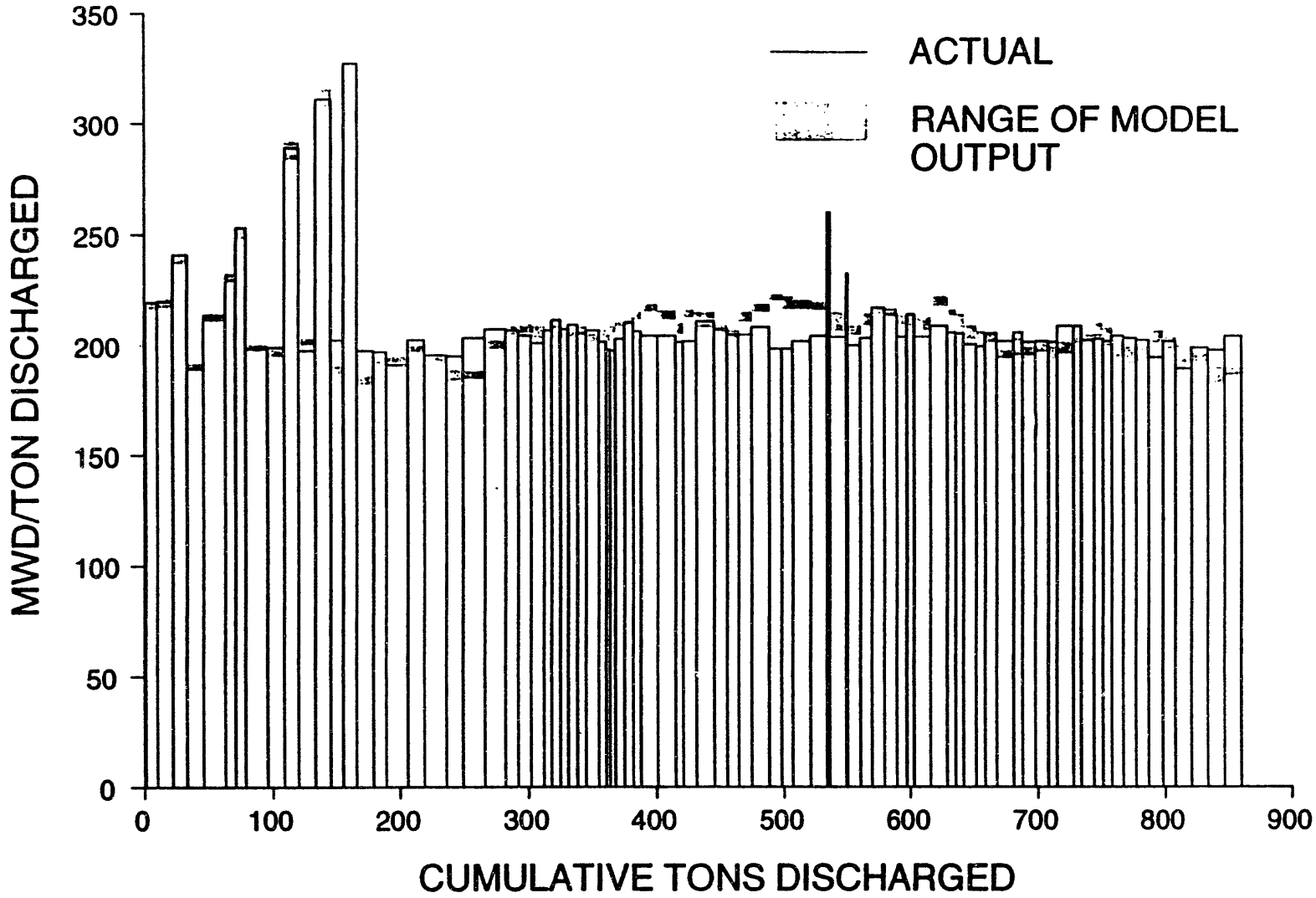

FIGURE A.4. Estimated Exposures of F Reactor Discharges

APPENDIX B

EVALUATION OF RELEASE FACTOR REFERENCES

APPENDIX B

EVALUATION OF RELEASE FACTOR REFERENCES

The following is an evaluated listing of principal Hanford references relating to iodine-131 fractions. They are listed in chronological order. They provide estimates of the fraction of iodine in the dissolver that was released to the dissolver off-gas line, was released in processing steps in the separations after dissolving, or to the fraction that was retained in the stack condensate after reaching the stack.

EVALUATED RELEASE FACTOR REFERENCES

1. Reference — Dreher (1944)

   Content — Early estimates from Oak Ridge (code name "Clinton") pilot operations of iodine and xenon to be expected at Hanford. Not all estimates turned out to be accurate.

   Release Factor — none

2. Reference — Seymour (1945)

   Content — Curie measurements of iodine-131 emitted from runs T-4-12-B7, T-5-1-B1, B2, and B3 were estimated:

Run	Iodine Emission
1	120
2	145
3	230
4	175

   The statement is made, "Results from the first four runs were not at all consistent with the previous set." These were the first few T Plant runs. With new dissolver off-gas lines and a new stack, it is likely the iodine was depositing on the new surfaces leading to lower releases than would be characteristic of later runs. Also, the measurement equipment was new and the accuracy subject to question.

   Value — none

3. Reference — Parker (1945a)

Content — This repeats the values above. The maximum Ci/ton is quoted as 230 with an average for January 1945 of 170 Ci/ton and monthly average of 270 Ci/ton for December 1944.

Release Factor — none

4. Reference — Dreher (1945)

Content — This early summary cites laboratory analysis of process solutions from dissolving through extraction and reduction. These studies indicated that 48% of the iodine in the irradiated metal stayed in solution and was not volatilized during dissolving. In part B under "Discussion" the author relates these laboratory studies to plant experience with the following statement: "As a result of this correlation, it can be predicted that at full power level (250 megawatt days per ton [comment: MWd/ton is burnup, not power], which corresponds to a concentration of 0.4 to 1.2 mg/liter of solution) about 80% of the iodine will be evolved during metal dissolution."

Release Factor — 0.80

5. Reference — Parker (1945b)

Content — "In the period 10/25/45 to 11/16/45, seven satisfactory runs of iodine emission and four xenon emissions were made. The I^{131} content was estimated at 4530 Ci from the fission yield data. The measured emission was 3245 Ci." This immediately implies a release factor of 3245/4530 = 0.72. This value is based on improved measurement techniques compared to the state of the art in References 2 and 4.

Release Factor — 0.72

6. Reference — Smith (1946)

Content — The purpose of this memo is to estimate how much iodine-131 could be recovered from the dissolvers. In the course of the discussion the following interpretation of "available data" is made: "We do not have firm experimental proof of the disposition of the I^{131} which goes into the dissolver but conclude from the data available that 85% goes out the stack, and 15% goes into the waste

tanks-10% in metal waste and 5% in stack drainage." This leads to an estimate of a release factor of 0.80, allowing for the 5% that drains into the bottom of the stack and is not emitted.

Release Factor 0.85

7. Reference Apple (1946)

Content Gives method of calculating iodine-131 content:

$$\frac{(P(kw) \times 3.1 \times 10^{13} \text{ fis/s/kw} \times .028 \text{ } I^{131}\text{/fission})}{3.7 \times 10^{10} \text{ dis/sec/Ci}}$$

This is 23.459 x P, about 3% less than 24.174 used in the HEDR estimate of iodine-131.

Concerning the accuracy of the iodine-131 in 292 Bldg: "In the opinion of those responsible for the equipment this value is considered good: agreement between experimental and theoretical has never been found to be better than 1 to 3-5."

"Although the quantity of stack drainage was determined during startup (December) on inactive metal dissolvings (1.5-4 gallons/hr), the following summary of meteorological and other data indicates that during the summer months, at least, little or no condensation takes place."

Release Factor none

8. Reference Miller (1946)

Content "The quantity of 8 day I^{131} per metal dissolving (1 metric ton) was calculated to be 140 curies (approximately 1 mg.). A review of previous work indicated that only about 10% of the iodine remains in the metal solution with the remainder going out with the stack gases."

Release Factor 0.90

9. Reference Seymour (1946)

Content "Some 4.7×10^5 curies of I^{131} and 2.2×10^5 curies of Xe^{133} have been discharged with current monthly rates of 7000 curies for iodine and 1000 curies for xenon." The HEDR estimate of the monthly average iodine-131 Ci processed in spent fuel for the eleven months preceding the

December date of this reference is 9793 Ci. During this entire period a nominal cooling time of 60 days was maintained, with an average for the period of 62 days, a maximum in June of 73 days and a minimum in September of 56 days. A release factor for this period would be 7000/9793 = 0.71.

Release Factor 0.71

10. Reference Work (1946)

Content "This includes all xenon, krypton and other rare gases and an estimated 85% of the iodine." "By far the largest fraction of the fission products in a batch of irradiated uranium is sent to the buried waste storage tanks. Only about 10% of the iodine and none of the inert gas activities follow this route, however." "Likewise, a small amount of mixed activities and perhaps 5% of the total iodine are caught in the stack drainage."

Release Factor 0.85-0.90 0.05 stack drainage

11. Reference Lauder (1947)

Content "The equipment in the Stack Monitor Building was operated on three occasions during the month. The measured amount of I^{131} evolved per run amounted to about 85% of the theoretical amount of 70 curies."

Release Factor 0.85

12. Reference Parker (1948)

Content "Some fraction of the total iodine content of the metal appears to escape during process stages other than dissolving. "...85% of the available I^{131} is released during dissolving and 10% goes to waste storage. The remaining 5% is presumably released during processing."

Release Factor 0.85 0.05 post-dissolution release

13. Reference Holm (1951)

Content "Before the iodine remaining in solution can be sent to a waste stream, about ten per cent of it is evolved in subsequent operations, thus contaminating canyon

ventilating air." Ten percent of the dissolved iodine was evolved in subsequent processing stages.

Release Factor none

14. Reference Burns and Kane (1952)

Content "Experience already gained in the Bismuth Phosphate Process plants indicated that about 80 per cent of the iodine present in irradiated uranium is evolved during the dissolving process."

Release Factor 0.80

15. Reference Kirkendall (1952a)

Content "Data obtained by the Stack Gas Disposal Group, Separations Technology Unit, indicated that approximately 5% of the iodine present in irradiated uranium slugs was evolved after the metal dissolution was complete and the metal solution left the dissolver tank[1]." Reference 1 was destroyed.

"At a spargent flow rate of 1.7 cc/min/ml (approximately 100 cu ft/min on a plant scale) about 90 per cent of the iodine present was removed in three hours at 95 degrees centigrade." This is a laboratory and not a plant result.

"Based on radioiodine analysis of metal solution sampled from the dissolver, sparging during reaction on seven cuts produced an average iodine evolution of 92.3 per cent of the total amount calculated to be present. Six control cuts without sparging during reaction averaged 86 per cent evolution of the total iodine calculated to be present. The average improvement in iodine evolution resulting from sparging during the dissolution reaction was 6.4 per cent and ranged from 0 to 14 percent." This is a measurement of the release factor of 86%. This technique of measuring the remaining iodine-131 is probably inherently more accurate than measuring evolved iodine in the stack.

The following values are quoted from Table I for the six cuts that were not sparged:

Push	Cut	I-131 Evolved (%)
10-24 F	F_d-16	83.9
11-25 D	D_d-34	89.0
11-15 D	D_d-10	80.7
12-21 F	F_d-40	88.5
2-14 D	D_d-1	86.1
2-19 B	B_d-19	87.2
	Average	85.9
	Standard Deviation	2.93

The method of calculating the iodine content of the fuel is given, and it includes an estimate of the average specific power of the slugs in each charge. This was obtained by knowing the burnup (MWd/ton) and the residence time of the fuel in the reactor which allows a true calculation of specific power by dividing burnup by the time in-pile.

Release Factor 0.86, 0.03 standard deviation on 6 samples. 5% of iodine-131 is evolved after dissolution.

16. Reference Kirkendall (1952b)

Content Seven batches of the dissolver acid solution were analyzed and 15% of the estimated iodine-131 content of the dissolver remained at the completion of the dissolution.

Release Factor 0.85

17. Reference Browne (1955)

Content "During the uranium metal dissolving, approximately 85% of the original I^{131} present is evolved...".

"The remaining 15% of the original I^{131} is transferred in the uranium nitrate solution through the uranium extraction process. Of this 15% residual I^{131} approximately two thirds would be evolved in subsequent processing and the remaining third would be carried out in waste solutions."

Release Factor 0.85 0.10 post dissolution processing

APPENDIX C

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

Document Number PNWD-2033 HEDR Document Title Iodine-131 Releases from the Hanford Site, 1944 Through 1947, Vol. 1 Text, Vol. 2 Data

Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
1.	K. J. Kopecky (KJK)	General Comment	This report is very well done.	NA - Thank you.
2.	M. L. Blazek (MLB)	General Comment	Well-written report. No comments regarding technical aspects.	NA - Thank you.
3.	M. A. Robkin (MAR)	General Comment	This is a very detailed report of the generation of the I-131 source term for the period 1944-1947. It represents a great, even "heroic," amount of work done under very difficult circumstances and the PNL contributors are to be commended. The Task direction was carried out with dedication and professionalism and the product is a credit to their efforts. I have some specific comments which I think will eliminate some potential points of confusion.	NA - Thank you.
4.	B. Shleien (BS)	General Comment	This is very fine work. Cal Heeb should be commended.	NA - Thank you.
5.	J. E. Till (JET)	General Comment	This is an excellent report and Cal Heeb, in particular, is responsible for bringing this part of the study firmly on track. The report is well written.	NA - Thank you.
6.	P. D. McGavran (PDM)	General Comment	Descriptive report well done.	NA - Thank you.
7.	W. A. Bishop (WAB)	General Comment	No comments.	

C.1

NA - No action.

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

Document Number PNWD-2033 HEDR Document Title Iodine-131 Releases from the Hanford Site, 1944 Through 1947, Vol. 1 Text, Vol. 2 Data

Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
8.	G. S. Roessler (GSR)	General Comment	Is this document intended for the public or for the TSP and Battelle? The first part, up to about page 4.4 and including equation 4.1, seems to be directed to the public. The writing is choppy and the equation presentation is awkward in that it is not presented in the usual way that a scientist would read it. From there on the document flows pretty well. I usually applaud the obvious efforts of the technical editors because they make a paper more readable, but this one seems to deviate from that. In fact, because of the inconsistencies in it (which I will point out in my editorial comments) it seems like the editing was not productive. I don't think a document such as this one should be directed toward the public. There are some sections that would be very difficult to make understandable.	The report was intended to be a technical report in which enough explanation would be provided to be readable by a general audience.
			If this report is to stand alone, the 100, 200, and 300 Areas should be defined early in the paper.	An explanation of the 100, 200 and 300 Areas was added to the Glossary on page xv.
			This document clearly shows that a tremendous amount of work was done to come up with the results. I am generally convinced that it is the best work possible with the existing data (and there is little likelihood that there is any more data). Cal and Maurice and others did a remarkable job on this. It should be published in a journal.	NA - Thank you.

NA - No action.

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

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Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
9.	JET	Page viii, Para. 3	I would delete this sentence or at least make it clear that the dose you are referring to thyroid dose. The point is, we know thyroid doses were high, what we do not yet know is how the iodine contributed to the effective dose relative to other radionuclides.	Last sentence changed to "...the effective whole body dose."
10.	GSR	Page vii, Para. 4, Line 2	Radiation should be radioactivity.	"Radiation" changed to "radioactivity."
11.	KJK	Page viii, Para. 2, Line 4	Would "The reactors released virtually no iodine-131" be more accurate"?	Changed to "virtually no."
12.	GSR	Page viii, Para. 2, Line 4	"Did not release iodine-131" -- not at all?	Changed to "virtually no."
13.	KJK	Page viii, Para. 3, Lines 1-2	Is I-131 really the "bulk of the radioactivity released"? Or is it the source of the bulk of the dose equivalent.	Statement revised. Iodine-131 is not the largest curie contributor to stack releases.
14.	BS	Page viii, ix	Notes for computer models. Acronym given only for first of these models - STRM. I suggest providing name and acronym for each. This is the best layout of the HEDR models and their roles in a simple manner that I have read. If you complete the job as I suggest, it would be a great source.	Titles and acronyms added for the other three HEDRIC models.
15.	KJK	Page ix, Para. 2, Lines 6-7	Recommend "...completeness of records allowed the uncertainty to be estimated for each value."	Recommended wording incorporated.

NA - No action.

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

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Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
16.	GSR	Page ix, Para. 3, Lines 5-6	"A constant amount" -- suggest "saturation."	Changed to "...reaches equilibrium and thereafter remains a constant amount."
		Page x, Para. 1, Line 2	"Proceeds at an easily calculated rate" -- suggest "with an 8-day half-life."	"Proceeds at an easily calculated rate" changed to "with an 8-day half life" as suggested. Although "half life" is a technical term, it is more generally understood than "saturation value," and the change makes the statement less vague.
17.	MAR	Page x, Para. 4, Line 2	The Phase I estimate for the amount of I-131 released does not have to be given as an "about" value. The estimate has been made and published as 406 kCi. Since the Reconstruction is given to 3 significant figures, the Phase I value should be given as published, 406 kCi.	Changed to 406,000 as suggested.
18.	KJK	Page x, Para. 3, Line 1	Recommend "As a result of this study, we estimate that the amount of iodine-131 released..."	Changed to "The estimated amount of iodine-131..."

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

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Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
19.	KJK	Page x, Para. 3	Here and elsewhere (e.g., page 7.1 of Volume 2), the definition of "standard deviation" is confusing. Line 4 refers to "SD" in Table S.1 as "one standard deviation *of the average value*...from 100 dependent runs." This would ordinarily be called a standard error rather than a standard deviation. Comparing the SDs with the minima and maxima in Table S.1 suggests that the SDs in the table are indeed standard deviations (i.e., they are roughly one-fourth of the difference between maximum and minimum; standard errors would be about one-fortieth). This needs to be corrected and clarified as necessary throughout both volumes of the report. Assuming that these are indeed standard deviations, then I recommend the following: "The values for each month are the mean ("Ci/month"), standard deviation ("SD"), maximum, and minimum from 100 independent runs of the Source Term Release Model (STRM). The values in Table S.1 for the total releases for each year and for the entire period 1944-1947 are based on the accumulated releases from the same 100 runs."	Changed text. Recommended wording incorporated.
20.	KJK	Page xii, Line 1	Recommend "...change the estimated magnitude of uncertainty..."	Replaced "the window" with "the estimated magnitude" as recommended.
21.	GSR	Page ix, Para. 1, Last line	Dose of iodine -- should be dose "from" iodine.	Replaced "of" with "from."

NA - No action.

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

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Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
22.	MAR	Page xi, Table S.1	Needs more explanation than is given by the footnote. In particular, an explanation is needed as to why the annual totals are not derivable from the monthly values. For example, in 1945, why are the annual curies not the simple sum of the monthly curies? Are the monthly Ci/month independent random variables from the Monte Carlo runs? The annual sigma value is much larger than the sigma derivable from the set of monthlies treated as independent variables. If a detailed explanation is given elsewhere in the document, it should be referenced in the Table.	Changes made as a result of comment 19 provide an explanation.
23.	BS	Page 1.4, Section 1.3.1	Is an excellent review of the production and separation processes. Indicate approximate percent of I-131 in stack gas (direct and via ventilation air) and remaining in neutralized waste.	NA - Amounts of I-131 released directly and via the canyon ventilation system are discussed in detail in Section 4.3.
24.	MAR	Page 1.1, Para. 3	The first sentence in the second paragraph is imprecisely stated. As written it implies that when a selected number of rods was discharged, plutonium production in all of the rods ended. Perhaps it could be stated as "The amount of plutonium in the uranium fuel rods increased as the reactor operated. When a group of rods reached the desired plutonium content, they were discharged from the reactor."	Wording clarified as requested.
25.	GSR	Page 1.1, Para. 1, Line 4	Back ground should be background.	Changed "back ground" to "background."

SUMMARY OF TECHNICAL STEERING PANEL COMMENTS AND BATTELLE PACIFIC NORTHWEST LABORATORIES RESPONSES

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Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
26.	MAR	Page 1.2, Para. 4, Line 2	The last figure I thought Bruce Napier quoted for the fraction of the dose due to the 1944-1947 release of I-131 was 98%. If so, that is a much stronger statement than "over 90%, even if the latter is true.	Agree. Changed.
27.	MAR	Page 1.3, 1st bullet, Last sentence	Replace "That data" with "Those data."	"That data" replaced by "The," "is" replaced by "are."
28.	GSR	Page 1.4, Para. 1, Line 5	Large graphite cubes each with...	Added "each" for clarification.
		Line 6	Delete sentence "Heat was produced... This is stated later and better as "thermal energy..."	"Heat was" replaced with "Neutrons were."
29.	MAR	Page 1.4, Para. 1, Line 6	Replace "Heat was produced by a neutron chain reaction in the uranium." by "Heat was produced by the fissioning of U-235 in the reactor." In addition, wherever fissioning is ascribed to uranium as a generic element, it should be replaced by U-235.	Addressed under comment 28.
30.	MAR	Page 1.5, Para. 2, Line 4	Add "horizontally" after "flowed."	Added "horizontally."
		Page 1.5, Last para., Line 5	Replace "displaced" with "pushed." This would explain why the refueling was called a "push."	Replaced "displaced" with "pushed."

NA - No action.

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Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
31.	GSR	Page 1.6, Para. 5, Line 3	"Canyon" -- put in glossary or refer to somewhere.	Replaced "canyon" with "building."
32.	KJK	Page 2.2, Para. 2, Line 1	Change "date" to "data."	Changed "date" to "data."
33.	GSR	Page 2.2, Para. 4, Line 4	"Original" is spelled wrong.	Spelling of "original" corrected.
34.	BS	Page 2.4, Para. 5, and Page 2.6, Para. 1	Appears that information for period missed by Lindvig and G.E. If true, state so (I note this is true - page 4.11).	Citation error corrected. "Lindvig 1945, 1946" changed to "Bird 1945."
35.	MAR	Page 2.6, Last line	Add "total" before "pile."	Added "total."
36.	KJK	Page 2.6, Para. 4, Line 3	Delete quote marks around "distribution function."	Quotes removed.
37.	MAR	Page 2.7, 1st para., Top of page	Some more words are needed to explain how RM predicts the I-131 content of the discharged fuel. In particular, how the discharged fuel batch is located with respect to its irradiation position in the reactor, and therefore to its operating power density. The discussion in Section 2.4 does not really give the full explanation of the algorithm in RM.	Appendix A provides detailed information on the reactor model. Added reference to Appendix A.

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38.	KJK	Page 3.1, Para. 3	The fact that the estimated uncertainty in the release data is relatively small does not by itself assure that "the computed value encompass the actual value with a high degree of confidence," or even (worded perhaps more carefully) that the range of computed values encompass the actual value. The accuracy objective cannot be proven to have been met. One must assume also that the various input parameter values are accurately estimated and their uncertainties reasonably represented. Also, in line 4, correct spelling of "uncertainties."	Replaced "degree of confidence" with "probability." Corrected spelling of "uncertainties."

NA - No action.

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39.	MAR	Page 3.1, Section 3.1	The fact that one S.D. was within 10% of the mean of the releases is a statement of the reproducibility of the calculation, not its agreement with "truth." The calculation does not sample from actual releases. Thus we have no assurance that the computed value encompasses the actual value. We have some good corroborating evidence in the comparison between calculated and reported discharge masses, but that is about all. It is also not obvious why the comparison with Anderson is "required." What or who requires it? The calculation reported in this report is much more detailed than Anderson's, and, I suspect, much more reliable. The comparability objective seems to have been set more due to historical reliance on Anderson than on any theoretical or engineering basis. If the comparison is strictly by fiat, then it should be made clear. If there is a theoretical basis, then that should be explained.	Changes made under comment 38 address the inability to compare with true values which are, as correctly stated in this comment, unknown. The comparison with Anderson was mandated by the scope of work and was included there for historical reasons. "The required" removed.
40.	GSR	Page 3.2, Para. 2, Line 3	What is meant by peer review?	Added paragraph defining peer review on Page 3.3.

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41.	GSR	Page 4.1, Para. 4	This equation is particularly poorly presented. Negative exponents should be used to avoid confusion. Consistency is needed. The last paragraph on the page defining the terms in the equation is written for a non-scientist and very hard to follow. In the last line, should it say right side of the equation instead of left?	Changed "left" to "right." Also changed macroscopic absorption cross section to product of N and microscopic absorption cross section.
42.	BS	Page 4.1	Mention source(s) of residual I-131.	NA - The derivation applies to intervals of constant power operation. The boundary conditions for the interval take care of any residual iodine-131 resulting from previous intervals.
43.	GSR	Page 4.2, Para. 3, Line 1	Put dis./sec/Ci as dis. sec^{-1} Ci^{-1} to avoid confusion.	Replaced "disintegration/ sec/Ci" with "dis. sec^{-1} Ci^{-1}."
44.	MAR	Page 4.2, Middle of page	Three significant figures for the energy yield per fission is not justified. Duderstadt and Hamilton (Nuclear Reactor Analysis) give 193 MeV/fission, and they give the breakdown by components. Their 3 s.f. is not justified either, given the range of values for components that they quote.	NA - The 201.72 MeV per fission is the number in the ORIGEN2 library. It is quoted for accurate source documentation for the iodine-131 calculation used in the document.
45.	MAR	Page 4.2, Eq. 4.2	Using the values given on the page, the coefficient comes out as 24,137 which rounds to 24,100. Only 24,000 is justified. The number will be larger if a smaller energy yield per fission is used.	NA - The number used in the calculations is 24174. 24200 changed to 24174.

NA - No action.

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Comment Number	Commenter	Page, Paragraph	Comment Summary	Resolution
46.	GSR	Page 4.25, Para. 1, Line 1	I guess this measurement of iodine in the stack was complex enough so that it was done only infrequently. Otherwise, why could it not be used to estimate iodine releases. This should be clarified in the document.	The measurement was infrequent as surmised in the comment. The technique is inherently less accurate than the method used by Kirkendal. In using release factors estimated from the Kirkendal data, a more accurate estimate of the released iodine-131 is achieved than would be possible were the stack measurements used (see p. 4.27).
47.	GSR	Page 4.3, Para 3., Line 6	Equation (3) should be (4.3).	Changed to 4.3.
48.	MAR	Page 4.3, Last para, Lines 2-3	The only explicit values given for the peaking factor is Table A.1 for the 25 ring model which gives values between 1.5 and 0.5. To refer to Appendix A for the purpose of page 4.3, explicit reference to the 244 ring model should be made.	Reference made to full 244-ring model as suggested.
49.	GSR	Page 4.4, Para. 3, Line 5	Pile power (DPP) -- why write it out when it was defined above? From here on there are a lot of inconsistencies with regard to use of an acronym especially PF. For example on 5.1 peaking factors should be shown as an acronym and then used as PF from there on.	Second daily pile power changed to DPP as suggested.