TRITIUM IN GROUND WATER AT THE IDAHO NATIONAL ENGINEERING LABORATORY, IDAHO

by Larry J. Mann and L. DeWayne Cecil

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 90-4090

Prepared in cooperation with the

U.S. DEPARTMENT OF ENERGY

Idaho Falls, Idaho

June 1990

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
INEL, MS 4148
P.O. Box 2230
Idaho Falls, ID 83403

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Bldg. 810, Box 25425
Denver, CO 80225

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

For readers who prefer to use International System (SI) units rather than units used in this report, the following conversion factors may be used:

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
curie (Ci)	3.7×10^{10}	becquerel
picocurie (pCi)	0.037	becquerel
millirem (mrem)	0.01	millisievert

To convert from picocuries per milliliter to Tritium Units, divide by 0.0032.

TRITIUM IN GROUND WATER AT THE IDAHO NATIONAL ENGINEERING LABORATORY

by

Larry J. Mann and L. DeWayne Cecil

ABSTRACT

From 1952 to 1988, approximately 30,900 curies of tritium were contained in wastewater generated by the ICPP (Idaho Chemical Processing Plant) and the TRA (Test Reactor Area) at the Idaho National Engineering Laboratory. The wastewater at the ICPP was discharged directly to the Snake River Plain aquifer through a disposal well until February 9, 1984, when routine use of the well was discontinued and an unlined infiltration pond was put into use. A second pond was put into use on October 17, 1985. Wastewater disposed at the TRA has been discharged to one to three infiltration ponds since 1952.

The average annual concentration of tritium in water from 26 selected wells at the INEL decreased from 250 pCi/mL (picocuries per milliliter) in 1961 to 18 pCi/mL in 1988, a decrease of 93 percent. The maximum tritium concentration was 844±5 pCi/mL in 1961 and 61.6±1.1 pCi/mL in 1988. Four factors are responsible for this decrease in tritium concentration: (1) a decrease in the amount of tritium disposed annually to ponds and wells from 1961 to 1988; (2) the change from the use of a disposal well to infiltration ponds at the ICPP; (3) radioactive decay; and (4) dilution from recharge.

INTRODUCTION

From 1952 to 1988, about 30,900 Ci of tritium were contained in wastewater disposed to wells and infiltration ponds at the INEL (Idaho National Engineering Laboratory). Most of the tritium was generated at two facilities, the ICPP (Idaho Chemical Processing Plant) and the TRA (Test

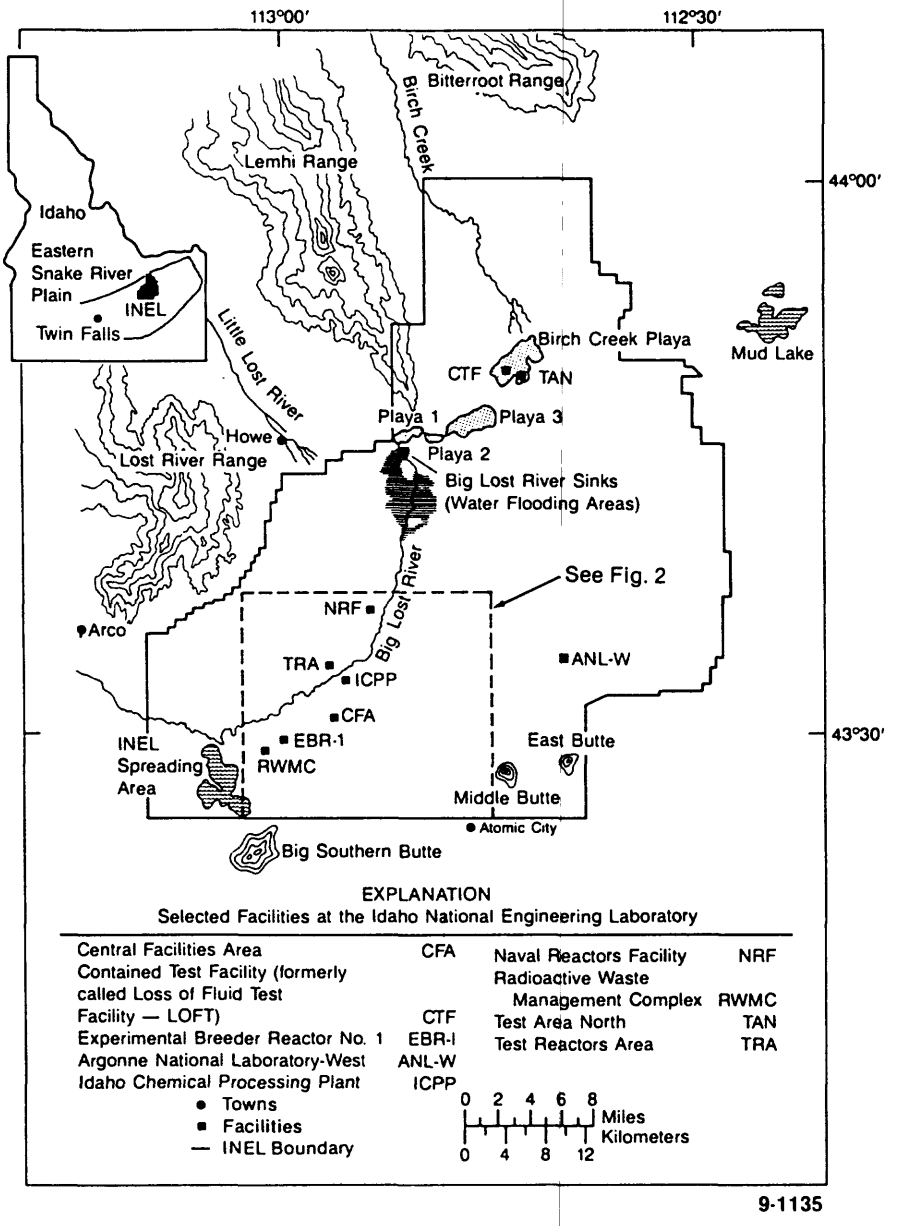

Figure 1.--Location of the Idaho National Engineering Laboratory and selected facilities.

Reactors Area). These facilities are about 2.5 mi apart and are in the south-central part of the INEL (fig. 1).

Wastewater containing tritium at the ICPP was routinely injected into the Snake River Plain aquifer through a 580-ft deep disposal well from 1953, when operations began, to 1984. Beginning February 9, 1984, the wastewater was routinely disposed to an infiltration pond; a second pond was put into use on October 17, 1985. The disposal well was used as an emergency backup to the disposal ponds in 1984-86. Wastewater from plant operations that flowed by gravity to the disposal well now must be pumped to the infiltration ponds. At the TRA, wastewater containing tritium has been disposed to one to three interconnected infiltration ponds since operations began in 1952. At both facilities, water disposed to the ponds infiltrates about 450 ft of unsaturated and saturated rock to the Snake River Plain aquifer.

Tritium disposed to the ICPP disposal well and to infiltration ponds at the ICPP and TRA can be detected in water from the Snake River Plain aquifer. In 1988, water from 31 wells in a 45-mi^2 area in the vicinity of the ICPP and TRA contained detectable concentrations of tritium. The size of the area in which tritium can be detected in ground water and the concentration of tritium are influenced by the 12.26-year half-life of tritium, variations in recharge to the Snake River Plain aquifer, variations in the tritium disposal rates, and changes in wastewater-disposal techniques.

This report describes the distribution and concentration of tritium in ground water and the factors that influence the migration of tritium in the Snake River Plain aquifer. The water-quality and hydrologic information on which this report is based was collected by the U.S. Geological Survey in cooperation with the U.S. Department of Energy's Idaho Operations Office. The data are available for inspection at the U.S. Geological Survey's INEL Project Office.

Physical Setting

The ICPP and TRA are in the south-central part of the 890-mi^2 INEL in

southeastern Idaho (fig. 1). The INEL was established in 1949 to build, test, and operate different types of nuclear reactors. Of the 52 reactors constructed, 13 are still operable. The INEL also is a leading center for nuclear safety research, defense programs, nuclear waste technology, and development of advanced energy concepts.

The INEL is on the eastern part of the Snake River Plain. Basaltic-lava flows intercalated with sedimentary deposits underlie the plain and make up the Snake River Plain aquifer, the major aquifer in southeastern Idaho. The aquifer provides the INEL's entire water supply and is a major source of irrigation, municipal, and industrial supplies on other parts of the plain. The depth to water in the aquifer ranges from about 200 ft below land surface in the northern part of the INEL to more than 900 ft in the southern part. At the ICPP and TRA, the depth to water in the aquifer is about 450 ft below land surface.

The general direction of ground-water movement at the INEL is to the southwest. Ground-water underflow in the aquifer at the INEL is primarily maintained by recharge in the northeastern part of the plain and from tributary drainages west and north of the INEL. From the recharge areas, the water moves under the INEL and eventually is discharged to springs along the Snake River near Twin Falls (Lewis and Jensen, 1985). Robertson and others (1974, p. 13) estimated the velocity of ground-water movement to be from 5 to 20 ft/day in the southern part of the INEL.

Streams at the INEL flow only in response to rainfall and snowmelt. The Big Lost River is the main drainage at the INEL and is a topographically closed basin. Flow in the river is regulated by Mackay Dam--about 40 mi upstream from Arco--and the INEL Diversion, which is in the southwestern part of the INEL. Water that is not diverted into the INEL spreading area (fig. 1), flows to the northeast toward the ICPP and TRA through the Lost River Sinks and into a series of playas. A large part of the water that flows onto the INEL infiltrates the permeable sedimentary deposits and basaltic rocks that underlie the river and the sinks, and recharges the Snake River Plain aquifer.

Previous Investigations

Many investigators have described the geology and hydrology of the Snake River Plain aquifer at the INEL. Robertson and others (1974) described the regional geology and hydrology, and the influence of liquid waste disposal on the geochemistry of water for 1952-70. Barraclough and Jensen (1976) reported on conditions from 1971 to 1973. Barraclough and others (1982) provided an update for 1974-78, Lewis and Jensen (1985) for 1979-81, and Pittman and others (1988) for 1982-85. Robertson (1974) described the development of a radioactive and chemical waste transport model for the Snake River Plain aquifer. These reports described the distribution of tritium in the aquifer resulting from the disposal of tritium at the ICPP and TRA.

Field Methods

Water samples from the Snake River Plain aquifer were collected at 26 selected wells near and downgradient from the ICPP and TRA and were analyzed for tritium (see figure 2 for locations of wells). Two methods were used to obtain water from the wells: (1) if a well was equipped with a dedicated pump, it was pumped and the samples were collected at the end of the discharge pipe or at a spigot in the discharge pipe; or (2) for ground-water monitoring wells not equipped with dedicated pumps, a remotely operated thief sampler was used to obtain a water sample. Since sampling for tritium in ground water began in 1960, the proportion of wells with dedicated pumps has increased significantly. In the 1960's a thief sampler was used to collect most water samples, whereas in the 1980's most wells were equipped with dedicated pumps.

Wells equipped with dedicated submersible or turbine pumps were pumped until the temperature, pH, and specific conductance of the water stabilized as described by Wood (1981) and Claassen (1982). When these properties of the water stabilized, suggesting that a steady-state water quality has been reached, a water sample was collected provided an ample volume of water had been pumped from the well. At most wells, a volume of water equivalent

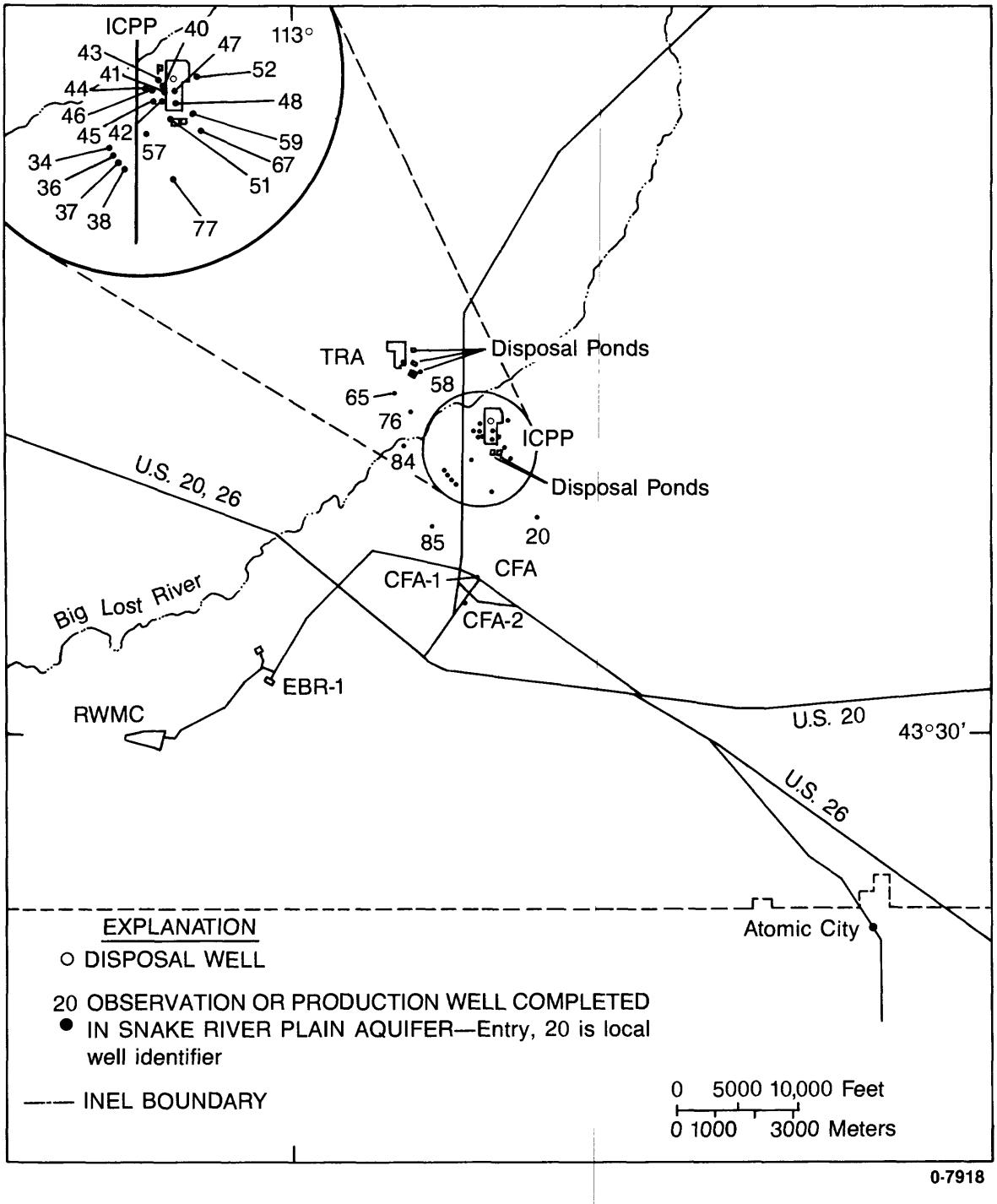

Figure 2.--Locations of observation wells completed in the Snake River Plain aquifer, and wastewater-disposal well and ponds in the south-central part of the Idaho National Engineering Laboratory.

to a minimum of 3 wellbore volumes was pumped from each well; at many wells, 5 to 10 wellbore volumes were pumped prior to the collection of a sample. The diameter of the wellbore, rather than the casing diameter, was used to calculate the minimum volume because of the potentially large difference between the two.

For wells without dedicated pumps, a thief sampler was lowered inside the well casing to a predetermined level. The thief sampler is constructed in such a manner that water passes through the sampler while it is being lowered to the sampling level. Once at the sampling level, the ends of the sampler are remotely closed, thereby trapping about 1 liter of water.

On the basis of drillers', geophysical, and fluid-conductivity logs, fracture zones have been identified in the basaltic rocks opposite perforations in the casing or in uncased intervals. Water likely moves through the fracture zones at a high velocity when compared with the velocity in unfractured zones. Each thief sample was taken at a predetermined level to obtain a sample that represented water moving through the aquifer rather than water that may have stagnated in the wellbore and casing opposite unfractured zones. The thief sampler was cleaned and rinsed with a pressurized spray of deionized water prior to and after use at each well.

Samples for tritium analyses were placed in 500-mL (milliliter) polyethelene bottles. The bottles were rinsed with at least one bottle volume of water withdrawn from the well being sampled. The unfiltered and untreated samples were hand carried to the U.S. Department of Energy's RESL (Radiological and Environmental Sciences Laboratory) for analysis.

Beginning in September 1987, field conditions at each site sampled were documented and a chain-of-custody record was maintained from the time of sample collection until the sample was delivered to the laboratory. The field books and chain-of-custody records are available for inspection at the U.S. Geological Survey's INEL Project Office.

Analytical Method

Water samples were analyzed for tritium by the RESL as described by Bodnar and Percival (1982). The direct liquid-scintillation counting method was used to analyze for tritium in water samples. This method is applicable for the determination of tritium artificially introduced into water by nuclear-power and waste-disposal facilities and is not sufficiently sensitive for determination of small natural tritium concentrations.

The method utilizes the conversion of energy emitted by a radioactive nucleus to light energy in a scintillating chemical. These scintillations for tritium are beta-particle emissions and are detected by a photomultiplier tube and amplified through a multichannel analyzer. The water samples are dissolved or dispersed in a standard volume of a proprietary mixture of organic solvent and a strong liquid detergent.

A 70-mL aliquot of each water sample was counted for gross gamma radioactivity prior to addition of the scintillating chemical to determine potential interferences from other radionuclides. Those samples greater than 100 counts per minute above background were distilled before addition of the scintillating chemical.

For each set of analyses performed in the laboratory, a reagent blank and an internal standard were prepared in addition to the target samples. A reagent blank was prepared by pipetting 10 mL of distilled water with no measurable tritium concentration into a 22-mL counting vial with 10 mL of the scintillating chemical. The internal standard was prepared by pipetting 9 mL of the reagent blank and 1 mL of standard tritiated water into a counting vial with 10 mL of the scintillating chemical. Each target sample was prepared by pipetting 10 mL of water into a counting vial with 10 mL of the scintillating chemical. All counting vials were securely capped and shaken until the water sample and scintillating chemical formed a gel. The reagent blank, standard, and samples were placed in the automatic counter of a liquid scintillation system and were counted for a total of 20 to 100 minutes. A tritium counting efficiency curve was obtained and tritium concentration for each sample was calculated.

For each tritium analysis, an associated analytical uncertainty, **s**, was calculated so that there was a 67-percent probability that the true tritium concentration in a sample was in the range of the reported concentration plus or minus the analytical uncertainty. For example, given an analytical result of 1.0±0.2 pCi/mL there is a 67-percent probability that the true concentration is in the range of 0.8 to 1.2 pCi/mL; at 2**s** or 1.0±0.4 pCi/mL, there is a 95-percent probability that the true concentration is in the range of 0.6 to 1.4 pCi/mL.

Guidelines for the Interpretation of Analytical Results

Guidelines for interpreting analytical results are based on an extension of the method described by Currie (1968). In the analysis for tritium, laboratory measurements are made on a target sample and a prepared blank. Instrument signals for the sample and the blank vary randomly. Therefore, it is essential to distinguish between two key aspects of the problem of detection: (1) The instrument signal for the sample must be greater than the signal for the blank to make the decision that tritium was detected; and (2) an estimation must be made of the minimum concentration that will yield a sufficiently large signal to make the correct decision for detection or nondetection of tritium most of the time. The first aspect of the problem is a qualitative decision based on signals and a definite criterion for detection. The second aspect of the problem is an estimation of the detection capabilities of a complete measurement process that includes hypothesis testing.

In the laboratory, instrument signals must exceed a critical level to make the qualitative decision whether tritium was detected. Tritium concentrations that equal 1.6**s** meet this criterion; at 1.6**s**, there is about a 95-percent probability that the correct decision--not detected--will be made. Given a large number of samples, as many as 5 percent of the samples with measured concentrations greater than or equal to 1.6**s**, which were concluded as being detected, might not contain tritium. These measurements are referred to as false positives and are errors of the first kind in hypothesis testing.

Once the critical level of 1.6s has been defined, the minimum detectable concentration can be established. Tritium concentrations that equal 3s represent a measurement at the minimum detectable concentration. For true concentrations of 3s or greater, there is a 95-percent or more probability of correctly concluding that tritium was detected in a sample. Given a large number of samples, as many as 5 percent of the samples with true concentrations greater than or equal to 3s, which were concluded as being not-detected, could contain tritium at the minimum detectable concentration. These measurements are referred to as false negatives and are errors of the second kind in hypothesis testing.

True tritium concentrations between 1.6s and 3s have larger errors of the second kind. That is, there is a greater than 5-percent probability of false negative results for samples with true concentrations between 1.6s and 3s and, although the tritium might have been detected, such detection may not be considered reliable; at 1.6s, the probability of a false negative is about 50 percent.

These guidelines are based on counting statistics alone and do not include systematic or random errors inherent in laboratory procedures. The values, 1.6s and 3s, vary slightly with background or blank counts, and with the number of gross counts for individual analyses. The use of the critical level and minimum detectable concentration aids the reader in the interpretation of analytical results and does not represent absolute concentrations of radioactivity which may or may not have been detected. In this report, if the tritium concentration was less than 3s, the concentration is considered to be below a "reporting level." The reporting level should not be confused with the analytical method detection limit, which is based on laboratory procedures. At small concentrations the reporting level approaches the analytical method detection limit; however, at larger concentrations they may be significantly different.

The analytical method detection limit for tritium has decreased since 1960 because of changes in analytical methodologies, the volume of the sample analyzed, equipment used in counting radioactive emissions, and counting times. For example, the analytical method detection limit reported

by the RESL ranged from about 5 pCi/mL in the early 1960's to 0.5 pCi/mL in 1988.

OCCURRENCE AND CHARACTERISTICS OF TRITIUM

Tritium, ^{3}H, is the heaviest and only radioactive isotope of hydrogen, ^{1}H. It is a naturally occurring radionuclide produced by cosmic-ray interactions at an estimated rate of 4 million Ci/year; the world inventory of natural tritium from cosmic-ray interactions is estimated to be 70 million Ci (National Council on Radiation Protection and Measurements, 1979). Atmospheric-weapons testing and nuclear reactors have increased the world inventory of tritium. Tritium produced from atmospheric-weapons testing reached a maximum of about 3.1 billion Ci in 1963 and will decay to a level equal to naturally occurring tritium by the year 2030 (National Council on Radiation Protection and Measurements, 1979).

Tritium concentrations in water from the Snake River Plain aquifer resulting from cosmic-ray interactions and atmospheric-weapons testing are less than 0.2 pCi/mL. In 1989, concentrations of tritium in water from 19 springs near Twin Falls (fig. 1) were less than 0.2 pCi/mL (Mann, 1989). Water from 12 irrigation and domestic wells about 65 mi southwest of the INEL contained tritium at concentrations ranging from less than the reporting level to 0.106±0.013 pCi/mL.

Tritium is formed in nuclear reactors by fission and by neutron activation of light elements such as boron and lithium. Estimates of the production rate by fission range from less than 12 to more than 20 Ci/megawatt(thermal)/day. Light element activation contributes 600 to 800 Ci/year to reactor coolant with an average annual release to the environment per 1,000 megawatts of electricity produced by light-water reactors of 63 Ci/year for boiling-water reactors and 830 Ci/year for pressurized-water reactors (National Council on Radiation Protection and Measurements, 1979).

Tritium decays to form a stable isotope of helium, ^{3}He, by emission of a beta particle with a maximum energy of 18 kiloelectron volts and an

average energy of 5.7 kiloelectron volts (National Council on Radiation Protection and Measurements, 1979). Tritiated water can be either of two chemical forms: $^{1}H^{3}HO$ or $^{3}H_{2}O$.

To evaluate the areal distribution and concentration of tritium in ground water, the half-life of tritium must be considered. Given that one-half of a specified amount of tritium will decay in 12.26 years, the fraction of tritium, R, remaining after one year of radioactive decay can be calculated using the following equation:

$$R^{12.26} = 0.5, \qquad (1)$$

where the exponent 12.26 is the half-life of tritium and 0.5 is the decimal fraction of the amount of tritium remaining after one half-life. When equation (1) is solved, R equals 0.945; the percentage is calculated by multiplying R by 100. It also follows that (1-R)×100 = 5.5 percent, which is the percentage of tritium that annually radioactively decays and the percentage of tritium that remains after n years is then equal to $(0.945^{n})\times100$.

When there is a relatively constant input of tritium, the amount of tritium in ground water will approach a steady-state condition; that is, the rate of radioactive decay will balance the rate of input and the total amount of tritium in the ground water will approach a constant value. The maximum amount of tritium that could be in the ground water when steady-state conditions are met can be mathematically described as

$$(0.945\times E_{c})+I = E_{c}, \qquad (2)$$

where: 0.945 is the proportional amount of tritium remaining after one year of radioactive decay; E_{c} is the curies of tritium in the aquifer at the time steady-state conditions are met; and I is the input of tritium in curies. By rewriting equation (2),

$$E_{c} = 18.2(I). \qquad (3)$$

Tritium Disposal from 1952 to 1988 and Amount of Tritium in the Snake River Plain Aquifer

The ICPP recovers uranium from spent reactor-fuel elements, mostly from government-owned reactors. Wastewater containing tritium was discharged to the ICPP disposal well or infiltration ponds. From 1953, when plant operations began, to 1988, about 21,100 Ci of tritium were contained in waste-water discharged to the disposal well and ponds.

Three nuclear reactors have been operated at the TRA since 1952. The Advanced Test Reactor currently operated at the TRA is a 250-megawatt pressurized-water reactor designed to test new fuels and materials that could help improve water-cooled reactor design. From 1952 to 1988, about 9,700 Ci of tritium were in wastewater discharged to the radioactive waste disposal ponds.

The amount of tritium discharged annually in wastewater at the ICPP and TRA is shown on table 1. From 1953 to 1988, the amount of tritium in waste-water at the ICPP ranged from 12 to 3,504 Ci/year and averaged 587 Ci/year; from 1952 to 1988 the amount of tritium in wastewater at the TRA ranged from 77 to 749 Ci/year and averaged 263 Ci/year. The combined amount of tritium contained in wastewater at the ICPP and TRA for 1952-88 ranged from 173 to 3,694 Ci/year and averaged 834 Ci/year.

Given that 834 Ci is the average annual amount of tritium in wastewater disposed at the ICPP and TRA, equation (3) can be used to calculate the maximum amount of tritium that could be in the aquifer when steady-state conditions are approached assuming that no tritium was lost to the atmosphere through evaporation from the disposal ponds.

$$18.2 \times 834 \text{ Ci} = 15{,}200 \text{ Ci} \qquad (4)$$

The amount of tritium in wastewater discharged to the ICPP disposal well and to ponds at the ICPP and TRA was not adjusted for evaporation. The amount that would have been evaporated is considered to be negligible or would be within the uncertainty of the estimates made for tritium in wastewater

Table 1.--Curies of tritium in wastewater disposed at the Idaho Chemical Processing Plant and the Test Reactors Area

[Curies of tritium in wastewater for 1952-61 are estimated based on plant operations. Source of data at the ICPP for 1953-61, K.R. Krivanek (Westinghouse Idaho Nuclear Co., written commun., 1989) and the TRA for 1952-61, Robertson and others (1974). Source of data for 1962-88, D.L. Litteer (EG&G Idaho, Inc., written commun., 1989).]

Year	ICPP	TRA	Total	Cumulative
1952	--	190	190	190
1953	456	190	646	836
1954	608	190	798	1,634
1955	808	190	998	2,632
1956	1,543	190	1,733	4,365
1957	969	190	1,159	5,524
1958	3,504	190	3,694	9,218
1959	2,565	190	2,755	11,973
1960	679	190	869	12,842
1961	590	190	780	13,622
1962	361	279	640	14,262
1963	1,084	353	1,437	15,699
1964	1,768	412	2,180	17,879
1965	97	328	425	18,304
1966	250	398	648	18,952
1967	861	424	1,285	20,237
1968	510	522	1,032	21,269
1969	125	749	874	22,143
1970	75	653	728	22,871
1971	59	342	401	23,272
1972	298	176	474	23,746
1973	32	184	216	23,962
1974	455	240	695	24,657
1975	43	260	303	24,960
1976	43	293	336	25,296
1977	734	140	874	26,170
1978	316	126	442	26,612
1979	225	105	330	26,942
1980	109	135	244	27,186
1981	359	191	550	27,736
1982	209	515	724	28,460
1983	436	203	639	29,099
1984	12	161	173	29,272
1985	393	261	654	29,926
1986	251	77	328	30,254
1987	215	128	343	30,597
1988	89	172	261	30,858
Average	587	263	834	

discharged from 1952 to 1961. For example: (1) evaporation of wastewater discharged to the disposal well would be negligible; and (2) the amount of tritium in wastewater in 1952-61 was estimated on the basis of plant operations for those years and would account for 44 percent of the tritium disposed to the well and ponds.

As an independent check to these calculations, the amount of tritium in the aquifer was computed using equation (1). The amount of tritium disposed annually from 1952 to 1988 was adjusted for radioactive decay year by year. The cumulative amount of tritium in the wastewater and the amount of tritium in the aquifer are shown on figure 3. The curve showing the curies of tritium in the aquifer clearly illustrates that a maximum of about 14,100 Ci of tritium were in the aquifer in 1970 and decreased to 10,160 Ci in 1988. The decrease in the curies of tritium in the aquifer was the result of the large differences in annual disposal rates, especially in the 1950's and 1960's. For example, 28 percent or 10,362 Ci of tritium were contained in wastewater disposed in 1956, 1958, 1959, and 1964.

The equation for calculating the number of years needed to obtain 99 percent of the steady-state value for a given production rate (Durrance, 1986, p. 286) is:

$$t_{99} = \left(\frac{\ln (1/1-0.99)}{\ln 2}\right) T_{\frac{1}{2}} \qquad (5)$$

where: t_{99} is the number of years needed to reach 99 percent of the steady-state value, and $T_{\frac{1}{2}}$ is the half-life of the radionuclide in years. The time needed to obtain 99 percent of the 15,200 Ci steady-state value for tritium, given a constant production rate, would be 81.5 years or approximately 7 half-lives. About 10,160 Ci, or 67 percent, of the 15,200 Ci of tritium is estimated to be in the aquifer at the INEL because not enough time has elapsed since 1952 for the system to reach the maximum calculated value.

The amount of tritium in the aquifer was also calculated using the 1970-88 disposal rates. The 1970-88 disposal rates were used because: (1) the curies of tritium in the aquifer was at a maximum in 1970 (fig. 3), and

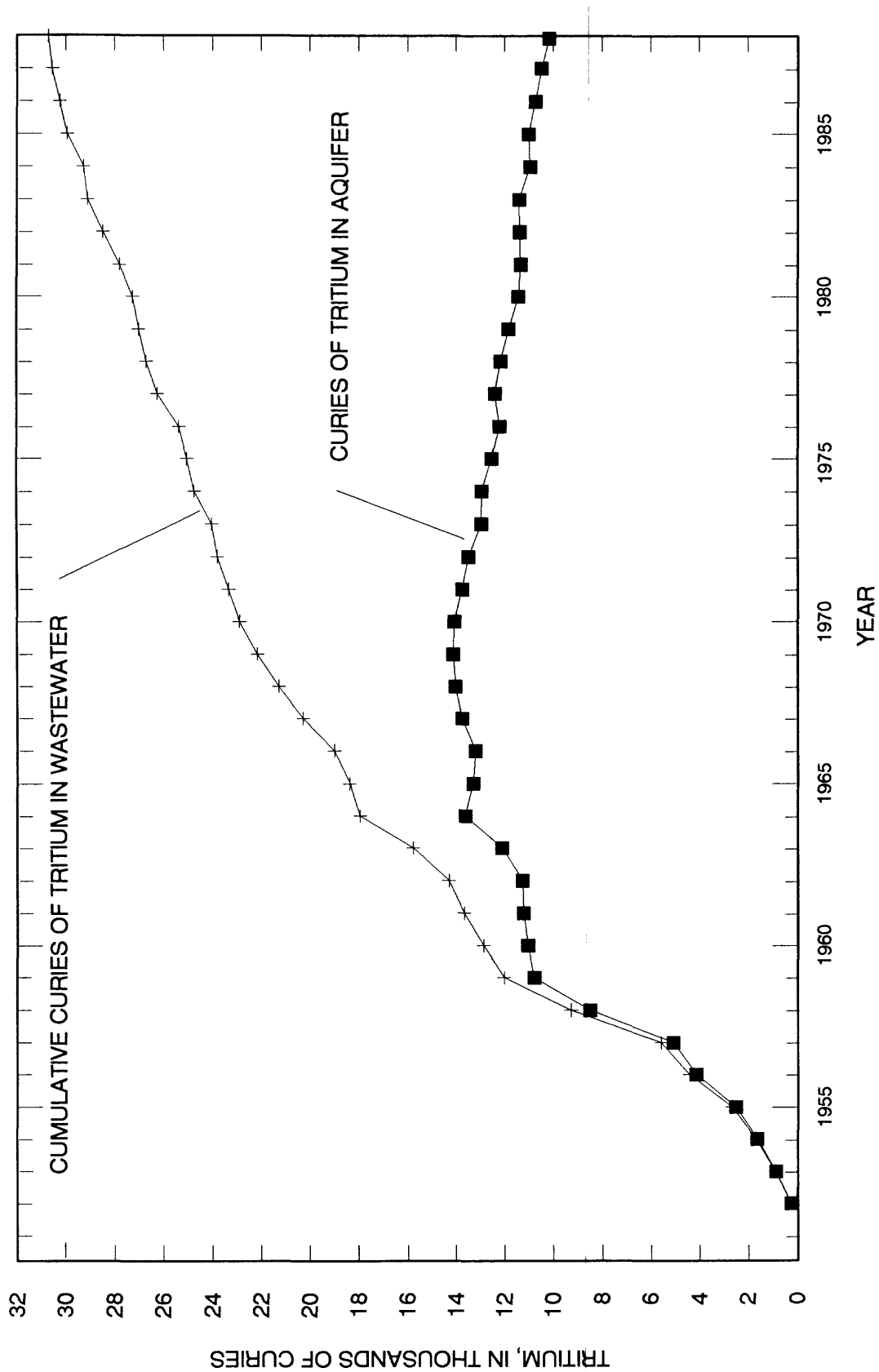

Figure 3.--Cumulative curies of tritium in wastewater and curies of tritium in water from the Snake River Plain aquifer after radioactive decay.

(2) the disposal rates in 1970-88 were smaller and were relatively constant when compared with those for 1952-69 (table 1). From 1970 to 1988, an annual average of 458 Ci of tritium was contained in wastewater disposed at the ICPP and TRA. If the average of 458 Ci/year of tritium is disposed in future years, the curies of tritium in the aquifer will approach a steady-state condition at about 8,400 Ci. Therefore, the 10,160 Ci of tritium contained in the aquifer will continue to decrease until a steady-state condition is approached at about 8,400 Ci; this assumes that the average annual tritium disposal rate for 1989 and subsequent years will equal the average rate for 1970 to 1988.

Concentrations of Tritium in Ground Water

Routine monitoring for tritium in water from the Snake River Plain aquifer began in 1961, although tritium analyses were performed as early as 1956. The concentration of tritium in ground water has varied because of changes in disposal rates, disposal techniques, recharge conditions,and radioactive decay. Tritium concentrations for selected years--1961, 1970, 1977, 1980, 1985, and 1988--are described in the following sections. These years were selected because: (1) 1961 was the first year of the comprehensive survey of tritium in the aquifer; (2) 1970 was the year when the total curies of tritium in the aquifer probably were at maximum and began to decrease due to radioactive decay and a decrease in the annual input; (3) 1977 was the first year of a 5-year period when there was little or no recharge from flow in the Big Lost River; (4) 1980 was a year when measured tritium concentrations subsequent to 4 years of minimal recharge from flow in the Big Lost River could be compared to those predicted by Robertson (1974); (5) tritium data for 1985 show the effects of the discontinuance of the ICPP disposal well for routine injection of tritiated water into the aquifer and show the effects of 4 years of recharge from comparatively large amounts of flow in the Big Lost River; and (6) 1988 shows current conditions. The tritium concentrations for each of the 6 years represent the conditions for October of each year; however, some of the wells were sampled up to 5 months prior to or after October in some years. Of the many wells sampled for tritium in 1961, 1970, 1977, 1980, 1985, and 1988, 26 were

selected to compare average tritium concentrations in ground water.

A large number of wells near and south of the ICPP and TRA consistently yield water with detectable concentrations of tritium. Most of these wells are open to the uppermost 50 to 200 ft of the Snake River Plain aquifer. Those wells open to the uppermost 200 to 500 ft of the aquifer do not yield water with detectable concentrations of tritium. For example, water samples collected by the U.S. Geological Survey from wells 83 and EBR-1 have not contained tritium greater than the reporting level. Well 83 penetrates about 250 ft of the aquifer and EBR-1 penetrates about 490 ft of the aquifer. This indicates that the vertical distribution of tritium chiefly is limited to the uppermost 200 ft of the aquifer. Composite water samples from these wells that penetrate more than about 200 ft of the aquifer contain tritium at less than the reporting level which may be because of dilution by water from deeper zones.

Tritium concentrations, 1961.--The first comprehensive survey of tritium in the Snake River Plain aquifer was made in 1961. From 1952 to 1961, an estimated 13,600 Ci of tritium were contained in wastewater disposed at the ICPP and TRA (fig. 3.) Radioactive decay had reduced the amount of tritium in the aquifer to about 11,200 Ci, a decrease of about 18 percent. By 1961, tritium injected into the ICPP disposal well had migrated south at least as far as the production wells at the CFA (Central Facilities Area). The analytical method detection limit for tritium in water in 1961 was approximately 5 pCi/mL; therefore, concentrations that were less than 5 pCi/mL could have been undetected in ground water about 1 to 3 mi south of the CFA. The areal extent and concentrations of tritium in the Snake River Plain aquifer in 1961 are shown on figure 4.

In 1961, the concentration of tritium in the Snake River Plain aquifer ranged from less than 5 to a maximum of 844±5 pCi/mL near the ICPP and 241±3 pCi/mL near the TRA. Tritium in the Snake River Plain aquifer near the ICPP and near the TRA formed two distinct "plumes" at concentrations greater than 5 pCi/mL (fig. 4). The average concentration of tritium in water from 26 selected wells that were sampled in 1961 was 250 pCi/mL (table 2).

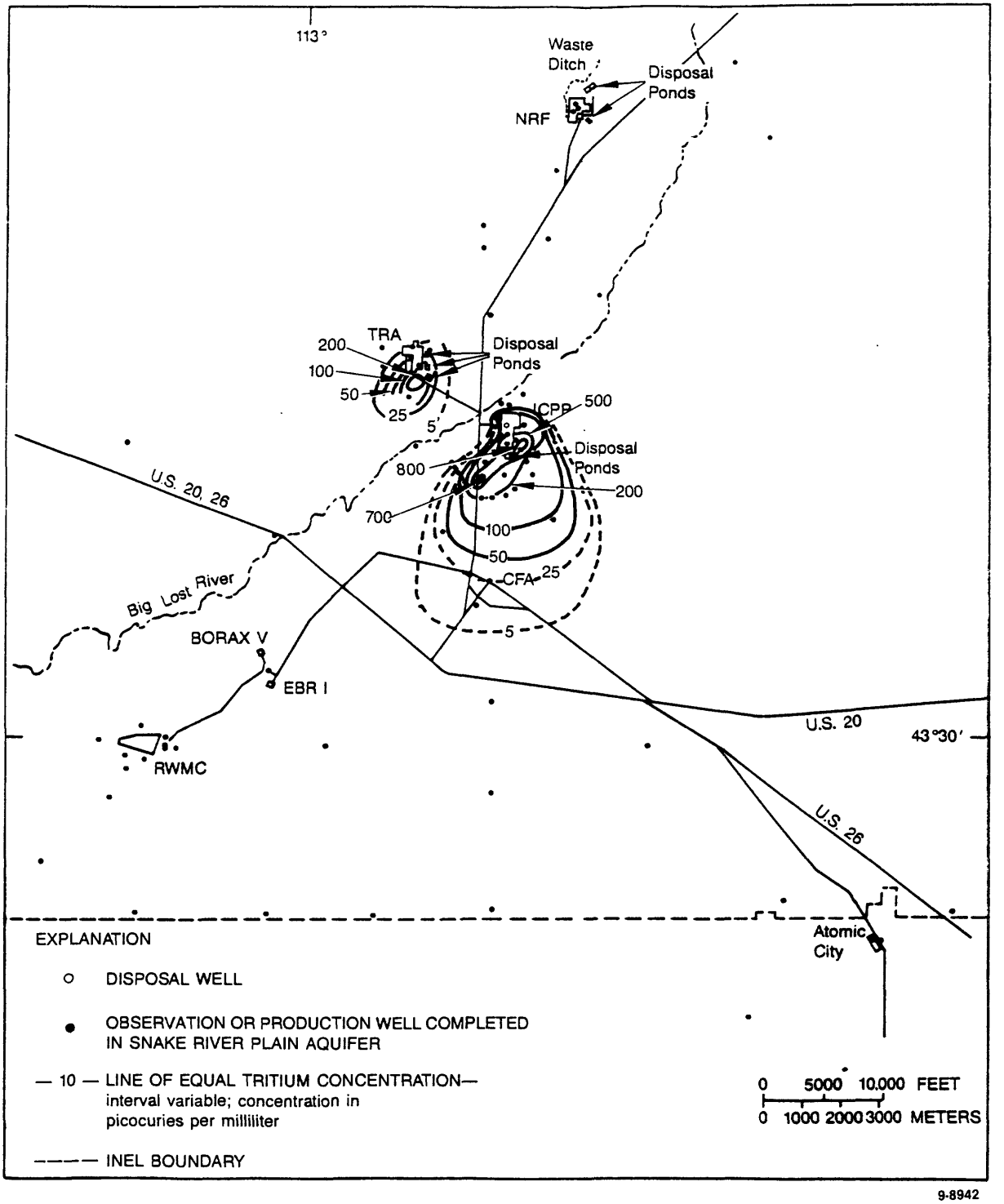

Figure 4.--Distribution of tritium in water from the Snake River Plain aquifer in the south-central part of the Idaho National Engineering Laboratory, 1961 (modified from Robertson and others, 1974).

Table 2.--Average concentration of tritium in water from 26 selected wells

[Average tritium concentration in picocuries per milliliter. Average was calculated on the basis of tritium concentrations in water from wells 20, 34, 36-38, 40-48, 51, 52, 57-59, 65, 67, 76, 77, 84, CFA-1 and CFA-2. See figure 2 for location of wells]

Year	Average concentration
1961	250
1970	101
1977	50
1980	56
1985	22
1988	18

Tritium concentrations, 1970.--By 1970, about 22,870 Ci of tritium were in water disposed to the ICPP disposal well and ponds at the TRA (fig. 3). Of this amount, about 14,050 Ci were in the Snake River Plain aquifer and about 8,820 Ci, or 39 percent, had undergone radioactive decay. From 1961 to 1970, the amount of tritium in the aquifer as a result of disposal practices at the INEL increased from 11,000 Ci to 14,000 Ci. For 1968-70, the amount of tritium in the Snake River Plain aquifer remained nearly constant at about 14,000 Ci; the annual curies of tritium decreased by radioactive decay were nearly equal to the annual curies of tritium input. The areal extent and concentrations of tritium in the aquifer in 1970 are shown on figure 5. The analytical method detection limit for tritium in water in 1970 was about 2 pCi/mL as compared to about 5 pCi/mL in 1961.

In 1970, the maximum concentration of tritium in the aquifer was 412±4 pCi/mL at well 43. The average tritium concentration in water from 26 selected wells sampled in 1970 was 101 pCi/mL (table 2). From 1961 to 1970, the maximum concentration of tritium had decreased by about 50 percent and the average for 26 wells had decreased by 60 percent. The decrease in tritium concentrations from 1961 to 1970 is attributed to the record high flows and the resultant recharge from the Big Lost River in 1969 (Robertson

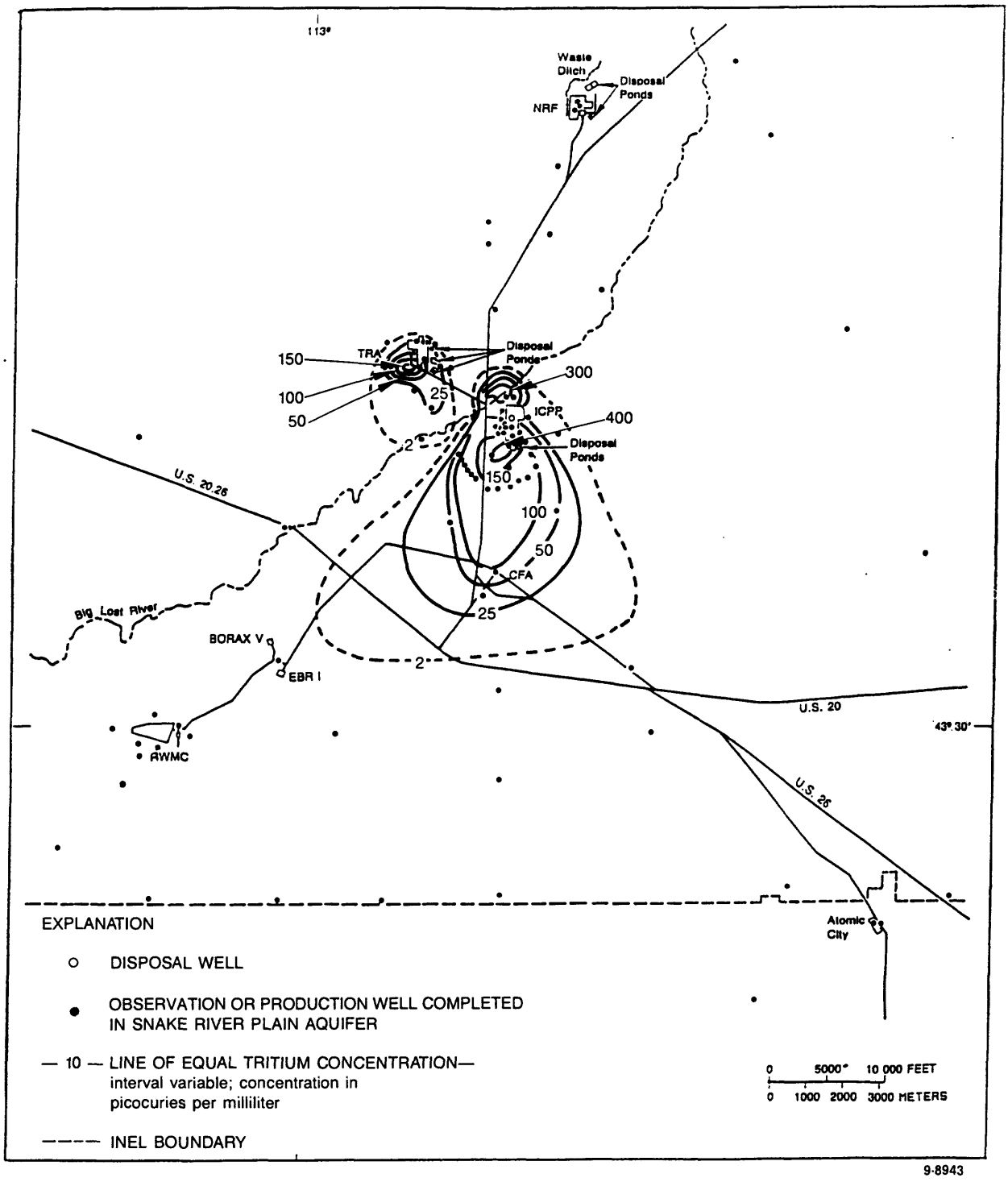

Figure 5.--Distribution of tritium in water from the Snake River Plain aquifer in the south-central part of the Idaho National Engineering Laboratory, 1970 (modified from Robertson and others, 1974).

and others, 1974, p. 174; and fig. 6). Tritium plumes in the aquifer near the ICPP and TRA had merged at concentrations of about 2 pCi/mL or less. Robertson and others (1974, p. 171) indicated that the plumes had merged by 1968 but were slightly separated at concentrations greater than 2 pCi/mL.

Although from 1961 to 1970 the maximum and average tritium concentrations in the aquifer decreased, by 1970, the tritium plume south of the ICPP had increased in size and migrated farther south. Near the CFA, ground water in areas that contained 5 to 25 pCi/mL of tritium in 1961, contained from at least 25 to 100 pCi/mL in 1970 (compare figures 4 and 5). For example, the tritium concentration in water from well CFA-1 increased from 15±2 pCi/mL in 1961 to 104±2 pCi/mL in 1970; water from well CFA-2 increased from 18±2 to 43±2 pCi/mL.

Tritium concentrations, 1977.--By 1977, about 26,170 Ci of tritium were in water disposed at the ICPP and TRA (fig. 3). Of the 26,170 Ci disposed, about 12,320 Ci remained in the aquifer and about 13,850 Ci of tritium had radioactively decayed. From 1970 to 1977, the amount of tritium in the aquifer decreased from 14,050 to 12,320 Ci, or about 12 percent, because of radioactive decay. The areal extent and concentrations of tritium in the Snake River Plain aquifer in 1977 are shown on figure 7. The analytical method detection limit for tritium in water was about 0.16 pCi/mL in 1977 as compared to 2 pCi/mL in 1970.

In 1977, the maximum concentration of tritium in the aquifer was 294±2 pCi/mL at well 40. The average tritium concentration in water from 26 selected wells was 50 pCi/mL (table 2). From 1970 to 1977, the maximum concentration in ground water had decreased by about 28 percent and the average for 26 selected wells had decreased by about 50 percent. The tritium plume originating at the ICPP had merged with the plume at the TRA; the concentration of tritium in water from wells in the area where the plumes had merged generally ranged from 2.4±0.2 to 9.0±0.4 pCi/mL.

Between 1970 and 1977, the tritium plume originating at the ICPP and TRA had migrated southward at concentrations less than about 10 pCi/mL. Prior to 1972, there were no deep wells near the RWMC (Radioactive Waste

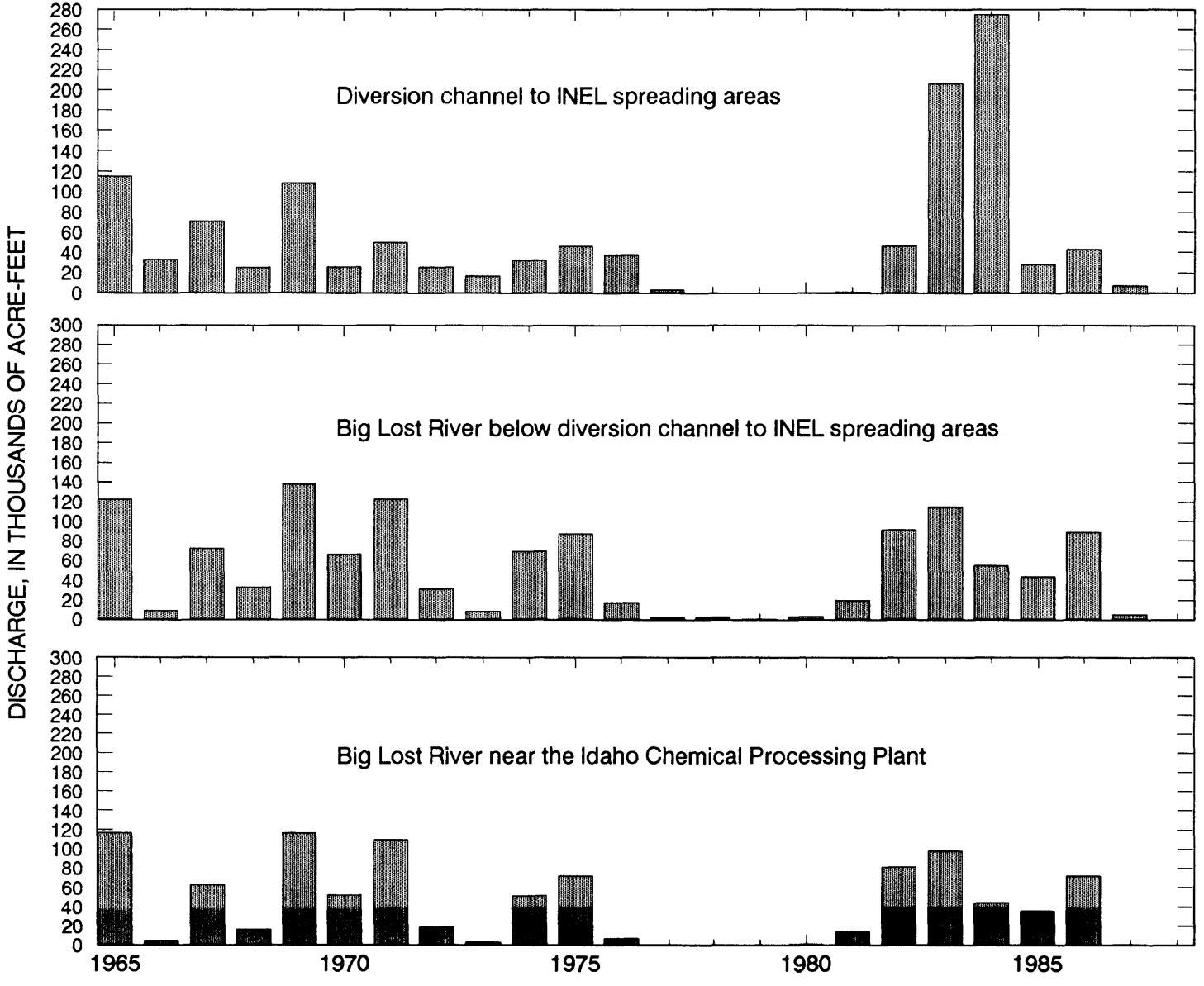

Figure 6.--Annual discharge of the Big Lost River at the Idaho National Engineering Laboratory.

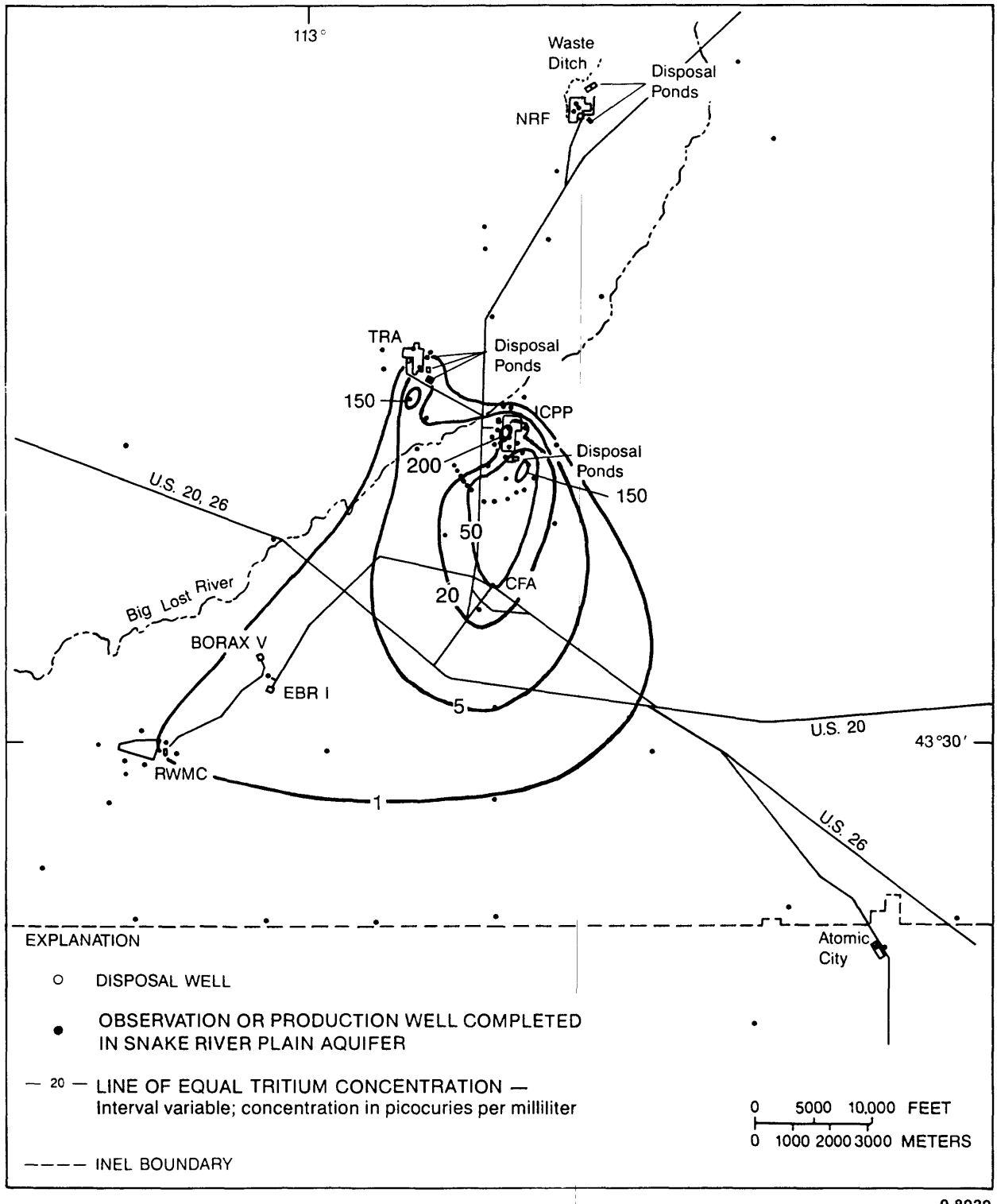

Figure 7.--Distribution of tritium in water from the Snake River Plain aquifer in the south-central part of the Idaho National Engineering Laboratory, 1977.

Management Complex). The first wells were drilled and sampling for tritium in ground water began in 1972. Tritium was regularly detected in water from well 90 and the RWMC production well beginning in 1975. In 1977, analyses indicated that tritium concentration in water from well 90 was 1.6±0.2 pCi/mL and the concentration in water from the RWMC production well was 1.4±0.2 pCi/mL. The tritium concentration in water obtained from wells CFA-1 and -2 decreased between 1970 and 1977; in 1970, water from CFA-1 and -2 contained tritium at concentrations of 104±2 and 43±2 pCi/mL, respectively, and, in 1977, contained tritium at concentrations of 47.2±0.6 and 29.8±0.6 pCi/mL, respectively.

Tritium concentrations, 1980.--The tritium in water disposed at the ICPP and TRA was approximately 27,200 Ci by 1980. Of this amount, about 11,350 Ci remained in the aquifer after radioactive decay. From 1977 to 1980, the amount of tritium in the aquifer decreased from 12,320 Ci to 11,350 Ci, or about 8 percent, because the curies of tritium decreased by radioactive decay exceeded the curies of tritium disposed. The areal extent of the tritium plume and concentrations of tritium in the Snake River Plain aquifer in 1980 are shown on figure 8.

In 1980, the maximum concentration of tritium in ground water was 184±6 pCi/mL in water from well 40. From 1977 to 1980, the maximum tritium concentration in ground water had decreased by 37 percent from 294±2 to 184±6 pCi/mL. The average tritium concentration in water from 26 selected wells increased 12 percent from 50 pCi/mL in 1977 to 56 pCi/mL in 1980 (table 2). The increase in the average tritium concentration in water from the 26 selected wells may be attributed to the lack of recharge from flow in the Big Lost River (fig. 6) and to the increase in the number of curies of tritium disposed at the ICPP between 1977 and 1980 (table 1).

A chemical solute-transport modeling study was conducted to project chloride and tritium plumes from 1972 to 1980 (Robertson, 1974). The projected tritium plume and a tritium plume based on well sample data are shown on figure 8. Two assumptions made by Robertson for the model projections were that tritium disposal ceased in 1973 and that the Big Lost River did not recharge the aquifer. Data collected subsequently do not

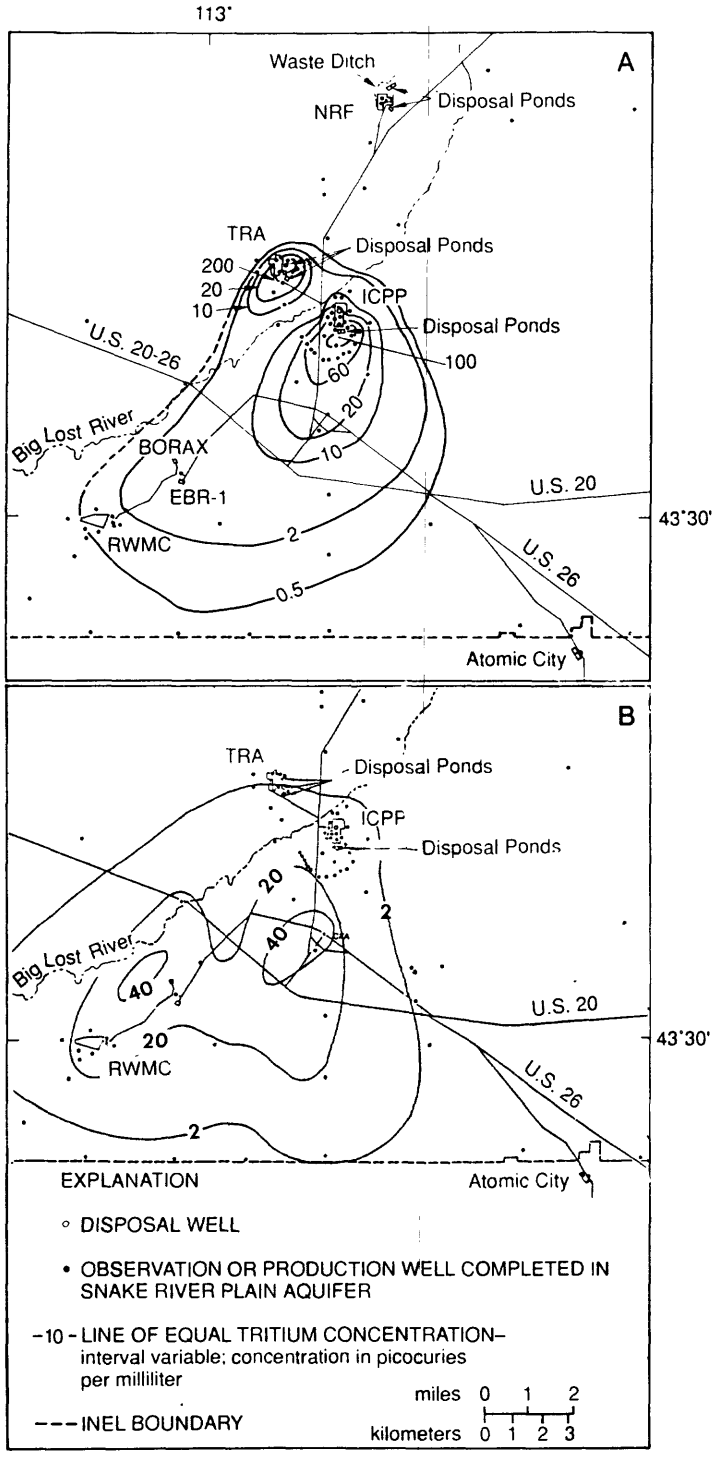

Figure 8.--Measured (A) and simulated (B) distributions of tritium in water from the Snake River Plain aquifer in the south-central part of the Idaho National Engineering Laboratory, 1980 [(A) modified from Lewis and Goldstein, 1982, p. 49, and (B) modified from Robertson, 1974, p. 32].

substantiate these assumptions. The actual tritium plume did not migrate as far south and west as the model predicted, due partly to the fact that some recharge to the aquifer from the Big Lost River did occur from 1973 to 1980 (fig. 6). Assuming that all measured discharge for the Big Lost River from 1973 to 1980 recharged the aquifer, approximately 330,000 acre-ft of water entered the aquifer from the Big Lost River. Robertson also assumed no vertical dispersion of tritium in the aquifer. Vertical dispersion of tritium over time should result in a plume that is smaller in lateral extent and concentration than the model-projected plume. The tritium concentrations in the plume drawn from field data are larger than the predicted tritium concentrations. This may be a result of the continued disposal of tritium at the INEL after 1973. From 1973 to 1980, an additional 3,440 Ci of tritium were in wastewater disposed at the INEL.

Tritium concentrations, 1985.--From 1952 to 1985, about 29,900 Ci of tritium were in water disposed at the ICPP and TRA (fig. 3). Of the 29,900 Ci of tritium disposed to the aquifer, about 18,900 Ci had radioactively decayed. From 1980 to 1985, radioactive decay had decreased the amount of tritium in the aquifer from about 11,350 to 11,000 Ci, or about 3 percent. The areal extent and concentrations of tritium in the aquifer in 1985 are shown on figure 9.

In 1985, the maximum concentration of tritium in the aquifer was 93.4±1.7 pCi/mL at well 65 (fig. 2). The average tritium concentration in water from 26 selected wells sampled in 1985 was 22 pCi/mL (table 2). From 1980 to 1985, the maximum concentration decreased by about 49 percent and the average for 26 selected wells decreased by about 61 percent.

In 1983, water obtained from wells 103, 105, and 108 using a thief sampler contained detectable concentrations of tritium for the first time since the wells were completed and monitoring began in September 1980. These wells are near the southern boundary of the INEL (fig. 2) and were installed to document concentrations of tritium in ground water at the boundary. In July 1983, water from well 103 contained 0.8±0.2 pCi/mL of tritium. Tritium concentrations in 10 water samples collected in October and November 1983 at depths from 588 to 750 ft below land surface were less

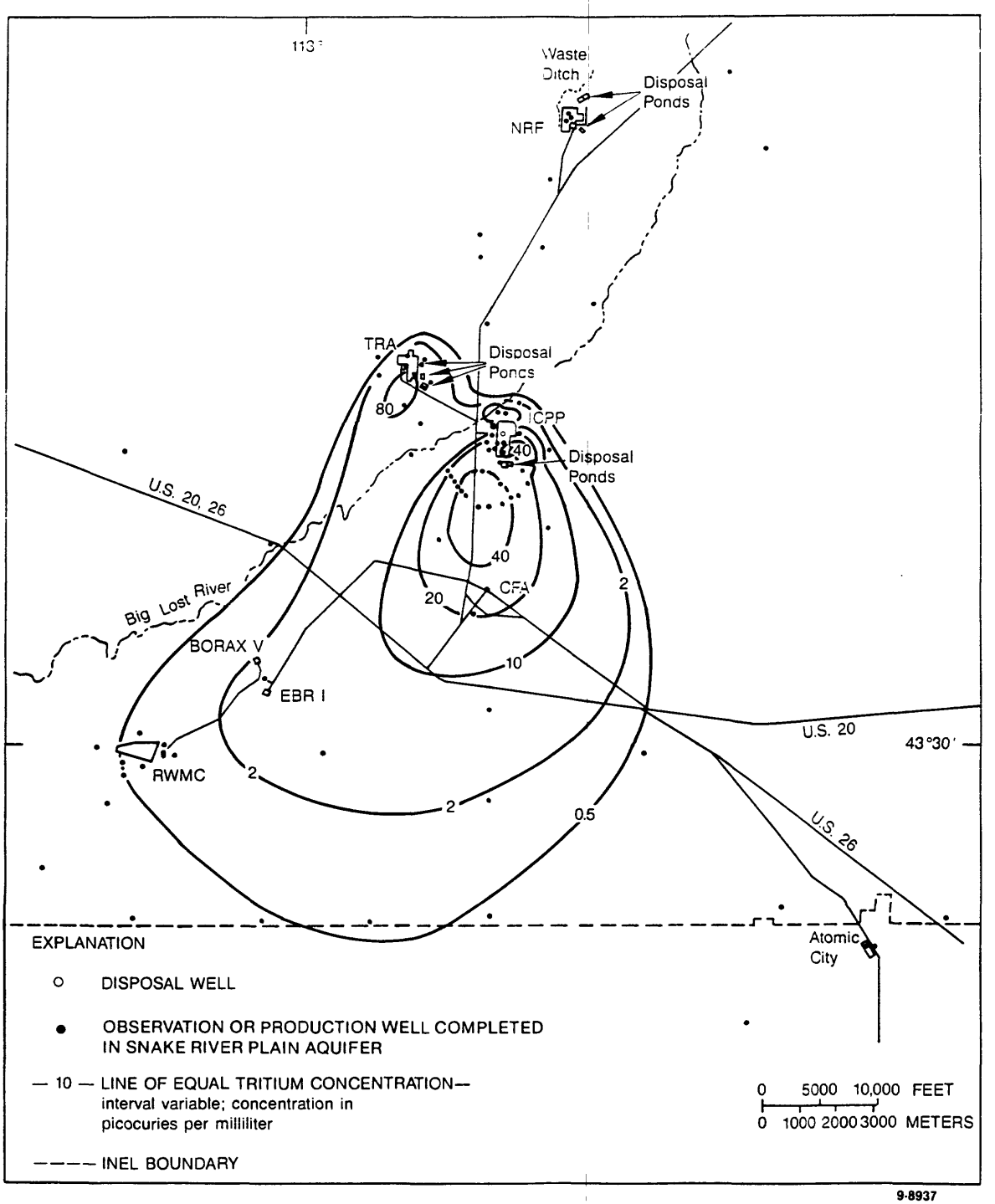

Figure 9.--Distribution of tritium in water from the Snake River Plain aquifer in the south-central part of the Idaho National Engineering Laboratory, 1985 (modified from Pittman and others, 1988).

than the reporting level; the depth to water in well 103 was 578 ft below land surface.

The detection of tritium in water from well 103 prompted an increased frequency of sampling at wells near the southern boundary of the INEL. In October and November 1983, 9 water samples were collected from well 105 at depths from 670 to 795 ft below land surface, and 11 water samples were collected from well 108 at depths from 610 to 755 ft below land surface; the depths to water in wells 105 and 108 were 666 ft and 603 ft, respectively. Tritium concentrations in water from well 105 ranged from less than the reporting level to 3.4±0.2 pCi/mL; tritium concentrations in three of the nine samples exceeded the reporting level and contained 1.2±0.1, 1.96±0.09, and 3.4±0.2 pCi/mL. Tritium concentrations in the 11 water samples collected from well 108 were greater than the reporting level; tritium concentrations ranged from 0.83±0.09 to 3.4±0.2 pCi/mL and averaged about 1.8 pCi/mL.

Because the occurrence of tritium was documented in water from wells 103, 105, and 108, dedicated submersible pumps were installed in the wells in late November or early December 1983. The dedicated pumps help to ensure that water samples representative of the aquifer are collected rather than water that may have been affected by storage in the wellbore. Tritium concentrations in water samples collected subsequent to the installation of the dedicated pumps were less than the reporting level except as follows: (1) two water samples collected on December 2, 1983 from well 108 contained 0.6±0.2 and 0.8±0.2 pCi/mL; and (2) a water sample from well 103 collected on July 12, 1985 contained 1.2±0.3 pCi/mL. Pittman and others, (1988, p. 48) reported that tritium in water from wells 105 and 108 was first detected in January 1984 and October 1985, respectively. However, the 1983 thief-sample data and the December 2, 1983, and July 12, 1985, pumped-sample data were not available to Pittman and others (1988) because of errors in a computerized data base; the errors were found during the preparation of this report.

Using a first arrival time of 1983 for tritium in water from wells near the southern boundary of the INEL, the calculated velocity of tritium

migration from the ICPP and TRA is about 4 ft/day; this velocity is consistent with the 4 to 5 ft/day velocity of tritium migration estimated by Pittman and others, (1988, p. 51).

Tritium concentrations, 1988.--The tritium in water disposed at the ICPP and TRA totaled approximately 30,900 Ci by 1988. Of the 30,900 Ci of tritium disposed, about 10,200 Ci remained in the aquifer after radioactive decay. From 1985 to 1988, the amount of tritium in the aquifer as a result of disposal practices at the INEL decreased from 11,000 to 10,200 Ci, or about 7 percent, because of radioactive decay. The areal extent of the tritium plume and concentrations of tritium in the Snake River Plain aquifer in 1988 are shown on figure 10.

In 1988, the maximum concentration of tritium in the aquifer was 61.6±1.1 pCi/mL in water from well 65. The average tritium concentration in water from 26 selected wells sampled in 1988 was 18 pCi/mL (table 2). From 1985 to 1988, the maximum tritium concentration in water from 26 selected wells had decreased by 34 percent and the average concentration had decreased 18 percent.

From 1986 to 1988, water from wells near the southern boundary of the INEL contained no detectable concentrations of tritium. The areal extent of the tritium plume and concentrations of tritium in the Snake River Plain aquifer decreased in 1988 compared with the areal extent and concentrations in 1985 (figs. 9 and 10).

Comparison of Tritium Concentrations with Drinking-Water Standards

The National Interim Primary Drinking Water Regulations (U.S. Environmental Protection Agency, 1976) set a maximum contaminant level of 4 mrem/year dose equivalent to the total body or any organ for manmade radioactivity. With the assumption of the ingestion of 2 liters per day of water for 1 year, the dose conversion factor in NBS Handbook 69 (U.S. Department of Commerce, 1963) can be used to calculate a concentration for tritium in drinking water of 20 pCi/mL (U.S. Environmental Protection

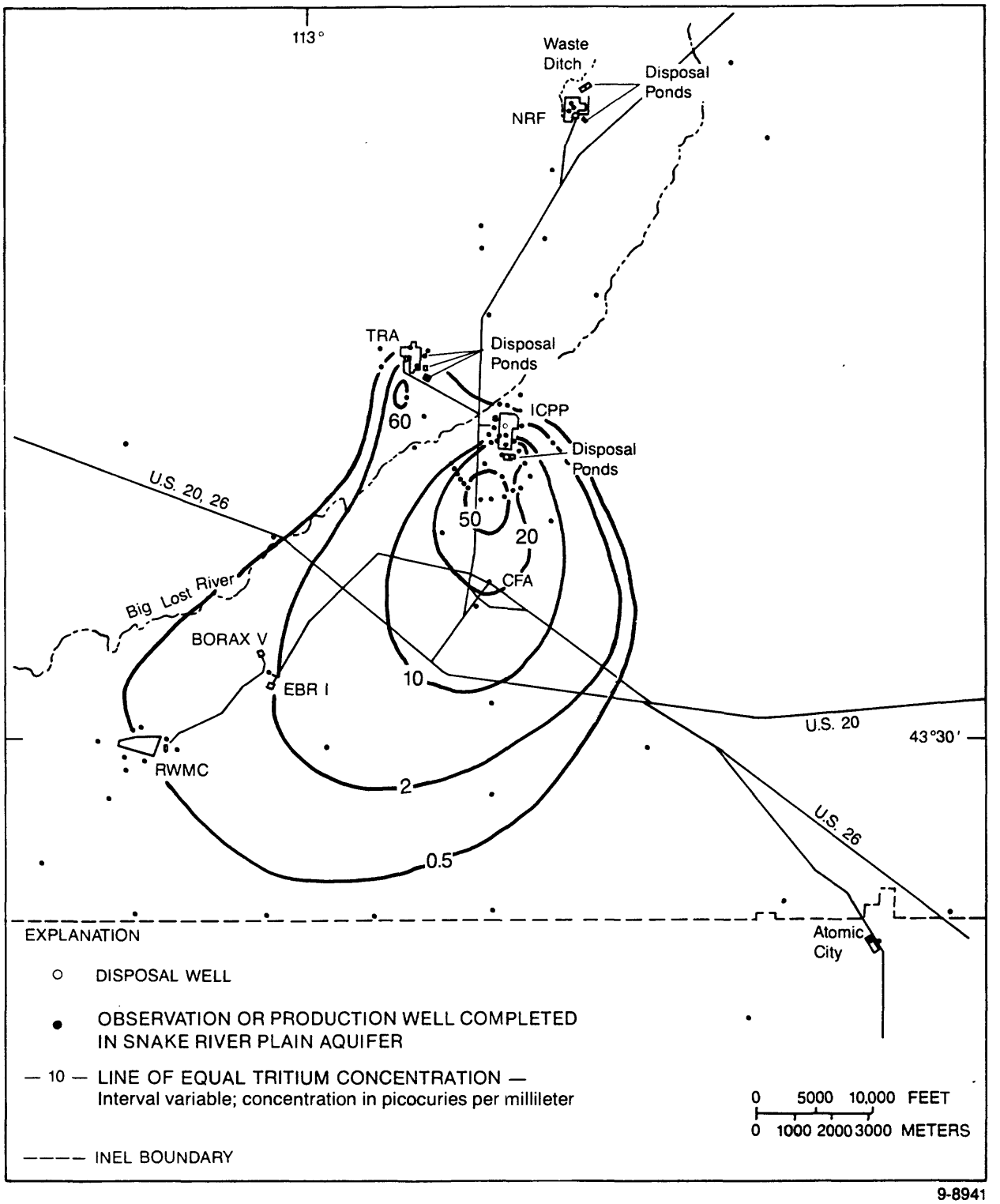

Figure 10.--Distribution of tritium in water from the Snake River Plain aquifer in the south-central part of the Idaho National Engineering Laboratory, 1988.

Agency, 1976). The dose conversion factors have been replaced by those of the International Commission on Radiological Protection (1978), which have been adopted by the U.S. Environmental Protection Agency, although there are some differences in the period of time over which the committed effective dose equivalent is calculated. New concentrations still based on 4 mrem/year for radionuclides have been proposed by the U.S. Environmental Protection Agency (1986). For the proposed standard, a concentration of 90 pCi/mL of tritium yields an effective dose equivalent of 4 mrem/year. Other radionuclides in the drinking water and the quantity of water consumed must also be considered in calculating the dose equivalent.

The U.S. Department of Energy has limited the effective dose equivalent from drinking water to 4 mrem/year. This is a small fraction of the 5,000 mrem/year effective dose equivalent recommended by the U.S. Environmental Protection Agency as a radiation protection standard for radiation workers that was approved on January 27, 1987 (The President, 1987); see also the recommendations of the National Council on Radiation Protection and Measurements (1987).

Currently, 27 wells are used to supply drinking water at the INEL. In 1988, water from one production well--CFA-1 (fig. 2)--had a tritium concentration that exceeded the existing maximum contaminant level of 20 pCi/mL. The tritium concentration in water from CFA-1 was 27.3±0.06 pCi/mL in 1988.

Seventy-six wells completed in and south of the ICPP and TRA at the INEL have been drilled and constructed for the purpose of monitoring ground-water levels and the quality of ground water. These wells are not used for drinking-water supplies. Fourteen of the monitoring wells yielded water with tritium concentrations that exceeded the existing maximum contaminant level of 20 pCi/mL. The tritium concentration in water for these 14 wells ranged from 25.2 to 61.6 pCi/mL and averaged 41.7 pCi/mL. However, no well yielded water with tritium concentrations that exceeded the proposed maximum contaminant level of 90 pCi/mL.

The part of the tritium plume in which concentrations exceeded 20

pCi/mL covered an area of about 3 mi^2 in October 1988 (fig. 10). If the proposed maximum contaminant level of 90 pCi/mL is adopted by the U.S. Environmental Protection Agency, no part of the tritium plume at the INEL would be included.

SUMMARY

Between 1952 and 1988, approximately 30,900 Ci of tritium were contained in wastewater disposed to wells and infiltration ponds at the INEL. Most of the tritium was generated and disposed at two facilities, the ICPP and the TRA. From 1953 to 1988, the amount of tritium in wastewater at the ICPP ranged from 12 to 3,504 Ci/year and averaged 587 Ci/year. From 1952 to 1988, the amount of tritium in wastewater at the TRA ranged from 77 to 749 Ci/year and averaged 263 Ci/year. The combined total of tritium in wastewater at these two facilities for 1952-88 ranged from 173 to 3,694 Ci/year and averaged 834 Ci/year.

Given the 12.26-year half-life of tritium and the average annual disposal rate of tritium of 834 Ci/year to the Snake River Plain aquifer, the maximum estimated amount of tritium that could be in the aquifer under steady-state conditions is 15,200 Ci. This calculation assumes that no tritium was lost to the atmosphere through evaporation from the disposal ponds. The largest amount of tritium in the Snake River Plain aquifer was 14,100 Ci in 1970 and decreased to 10,160 Ci in 1988. The 10,160 Ci of tritium in 1988 is about 67 percent of the calculated maximum amount, given the average annual input rate at the INEL, because there has not been enough time since 1952 for the system to reach a steady-state condition--which is 81.5 years or approximately 7 half-lives.

The average annual concentration of tritium in water from 26 selected wells at the INEL decreased from 250 pCi/mL in 1961 to 18 pCi/mL in 1988, or 93 percent. In 1961, the maximum tritium concentration in ground water at the INEL was 844±5 pCi/mL. In 1988, the maximum tritium concentration in ground water was 61.6±1.1 pCi/mL. Four factors responsible for the decrease in tritium concentration in ground water were: (1) the 1961-88 decrease in

the amount of tritium disposed annually to ponds and wells; (2) the change from the use of the ICPP disposal well to infiltration ponds; (3) radioactive decay; and (4) dilution from recharge.

Twenty-seven wells are used to supply drinking water at the INEL. In 1988, water from only one production well--CFA-1--had a tritium concentration that exceeded the maximum contaminant level of 20 pCi/mL set by the U.S. Environmental Protection Agency. The tritium concentration in water from CFA-1 was 27.3±.06 pCi/mL.

REFERENCES CITED

Barraclough, J.T., and Jensen, R.G., 1976, Hydrologic data for the Idaho National Engineering Laboratory site, Idaho, 1971 to 1973: U.S. Geological Survey Open-File Report 75-318 (IDO-22055), 52 p.

Barraclough, J.T., Lewis, B.D., and Jensen, R.G., 1982, Hydrologic conditions at the Idaho National Engineering Laboratory, Idaho--emphasis, 1974-1978: U.S. Geological Survey Water-Supply Paper 2191, 52 p.

Bodnar, L.Z., and Percival, D.R., 1982, Analytical Chemistry Branch Procedures Manual--Radiological and Environmental Sciences Laboratory: U.S. Department of Energy Report, IDO-12096.

Claassen, H.C., 1982, Guidelines and techniques for obtaining water samples that accurately represent the water chemistry of an aquifer: U.S. Geological Survey Open-File Report 82-1024, 49 p.

Currie, L.A., 1968, Limits for qualitative detection and quantitative determination--Application to radiochemistry: Analytical Chemistry, v. 40, no. 3, p. 586-593.

Durrance, E.M., 1986, Radioactivity in geology--principles and applications: New York, John Wiley and Sons, 441 p.

International Commission on Radiological Protection, 1978, Limits for intakes of radionuclides by workers: New York, International Commission on Radiological Protection Publication 30, Supplement to Part 1, Pergamon Press, p. 202-203.

Lewis, B.D., and Goldstein, F.G., 1982, Evaluation of a predictive groundwater solute-transport model at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 82-25, IDO-22062, 71 p.

Mann, L.J., 1989, Tritium concentrations in flow from selected springs that discharge to the Snake River, Twin Falls-Hagerman area, Idaho: U.S. Geological Survey Water-Resources Investigations Report 89-4156 (DOE/ID-22085), 20 p.

National Council on Radiation Protection and Measurements, 1979, Tritium in the environment: National Council on Radiation Protection and Measurements Report No. 62, 125 p.

---- 1987, Recommendations on limits for exposure to ionizing radiation: National Council on Radiation Protection and Measurements Report No. 91, 72 p.

Pittman, J.R., Jensen, R.J., and Fischer, P.R., 1988, Hydrologic conditions at the Idaho National Engineering Laboratory, 1982 to 1985: U.S. Geological Survey Water-Resources Investigations Report 89-4008 (DOE/ID-22078), 73 p.

Robertson, J.B., 1974, Digital modeling of radioactive and chemical waste transport in the Snake River Plain aquifer at the National Reactor Testing Station, Idaho: U.S. Geological Survey Open-File Report (IDO-22054), 41 p.

Robertson, J.B., Schoen, Robert, and Barraclough, J.T., 1974, The influence of liquid waste disposal on the geochemistry of water at the National Reactor Testing Station, Idaho: U.S. Geological Survey Open-File Report (IDO-22053), 231 p.

The President, 1987, Radiation protection guidance to Federal agencies for occupational exposure--approval of Environmental Protection Agency recommendations: U.S. Federal Register, v. 52, no. 17, p. 2822-2834.

U.S. Department of Commerce, 1963, Maximum permissible body burdens and maximum permissible concentrations of radionuclides in air and water for occupational exposure: U.S. Department of Commerce NBS Handbook 69, 95 p.

U.S. Environmental Protection Agency, 1976, National interim primary drinking water regulations: U.S. Environmental Protection Agency Report EPA-570/9-76-003, 159 p.

---- 1986, Water pollution control, National primary drinking water regulations; Radionuclides--Advance notice of proposed rulemaking: U.S. Federal Register, v. 51, no. 189, p. 34836-34862.

Wood, W.W., 1981, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 1, Chap. D2, 24 p.