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Methodology for Estimating Radiation Doses Due to Tritium and Radiocarbon Releases

by
D. A. Baker
J. K. Soldat

September 1976

Prepared for the Energy Research and Development Administration under Contract E(45-1)-1830

Battelle
Pacific Northwest Laboratories

BNWL-2020

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PREFACE

Fusion reactor technology has developed far enough to expect laboratory demonstration of practical levels of fusion employing the D-T reaction to occur in the early 1980s. Following that demonstration, and depending upon the national priorities for energy from D-T fusion, construction and operation of experimental reactors and demonstration power reactors could occur before the end of this century. Operation of the first commercial power plants could then follow, starting about 2010.

Development and adoption of a new power system eventually will require a description of the environmental effects in an environmental statement providing a comparison to the effects of competitive systems. In anticipation of that statement, an environmental analysis (BNWL-2010) has been prepared for the ERDA Division of Magnetic Fusion Energy. That analysis estimates the environmental effects of constructing and operating D-T fusion reactors as an economically competitive source of electricity in the 21st century.

The analysis has four primary purposes:

1. To describe the general nature of the environmental effects,
2. To determine current ability to estimate the effects,
3. To determine methods for reducing the effects, and
4. To determine research necessary for increasing capability to define and reduce the effects.

Timely identification of needed research and methods for reducing effects will permit the performance of that research and the revision of conceptual fusion power plant designs before preparation of the program environmental statement. This would improve the quality of the environmental statements and could reduce the estimated adverse environmental effects due to fusion power plants.

The environmental analysis (BNWL-2010) concludes that the following assumed characteristics are the best set for the first operating fusion power plants:

- The D-T fusion reaction
- Large quantities of activation products
- Kilogram quantities of tritium in the plant systems
- Massive reactor structures
- Large lithium inventories
- Large inventories of liquid metals and salts
- Standard electricity generation
- Standard radioactive waste systems
- Large magnetic fields
- A self-contained fuel cycle
- Rural siting

Using these characteristics a reference reactor was analyzed to determine the environmental effects by using available concepts of plant subsystems designs that control interactions with the environment or by assumption that best current technology would be used in subsystems design.

Because this analysis does not take into account advances in both fusion and waste control technology during the next thirty years, the estimated effects probably are significantly higher than the actual effects will be for the first fusion power plants. The estimated environmental effects should be interpreted only as being the probable upper limit for the actual effects.

Preparation of the fusion power plant environmental analysis required development and use of specially developed data and analysis methods not used in the preparation of current environmental statements for fossil and fission power plants. These data and analysis requirements are documented in a series of reference topical reports to make this information publicly available and to assure understanding of the basis for the conclusions made in the environmental analysis.

These reference topical reports summarize the state-of-the-art as applicable to preparation of environmental statements for fusion power plants. They present the data and analytical techniques used in the environmental analysis to estimate the interactions with the environment and the resultant environmental effects. This information then was analyzed for adequacy and the need was determined for additional research to assure satisfactory ability to prepare environmental statements for the fusion development program and experimental facilities in the early 1980s. Estimated environmental effects are presented in these reference documents only as necessary to illustrate use of the data and analytical techniques.

This report is one of those reference documents for the environmental analysis. The other documents in this series contain more details of the power plant concepts and the probable environmental effects of fusion power plants with the assumed characteristics listed above. These documents are available through the National Technical Information Service:

An Environmental Analysis of Fusion Power to Determine Related R&D Needs, BNWL-2010

Review of Fusion Research Program: Historical Summary and Program Projections, BNWL-2011

Fuel Procurement for First Generation Fusion Power Plants, BNWL-2012

Current Fusion Power Plant Design Concepts, BNWL-2013

Reference Commerical Fusion Power Plants, BNWL-2014

Siting Commercial Fusion Power Plants, BNWL-2015

Materials Availability for Fusion Power Plant Construction, BNWL-2016

Projected Thermodynamic Efficiencies of Fusion Power Plants, BNWL-2017

Tritium Source Terms for Fusion Power Plants, BNWL-2018

Management of Nontritium Radioactive Wastes from Fusion Power Plants, BNWL-2019

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Biomagnetic Effects: A Consideration in Fusion Reactor Development, BNWL-1973

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SUMMARY

Although the exact release rates of tritium (^{3}H) and carbon-14 to the environment from a fusion power plant are not known, unit dose rates from postulated releases to air or to surface water can be calculated for a hypothetical individual and for population groups. Assuming a tritium release of 1 curie per year (Ci/yr) as HTO to the atmosphere, a hypothetical maximum individual residing near a fusion power plant might receive a dose rate of 2×10^{-3} millirem per year (mrem/yr). Assuming a 1 Ci/yr release to surface waters, this individual might receive a dose rate of 1.5×10^{-5} mrem/yr. The dose rate to the population of the world including the United States and the regional population was estimated to be 1×10^{-2} man-rem/yr from the release to the atmosphere and 6×10^{-2} man-rem/yr from the release to surface waters.

Dose rates from releases of 1 Ci/yr of carbon-14 to the atmosphere were estimated to be 0.4 mrem/yr to the bone of the hypothetical maximum individual and 2 man-rem/yr to the total body of the world population. Because of the persistence of carbon-14 in the environment and the fact that carbon is a major constituent of any living thing, efforts should be made to eliminate those releases with available technology such as double containment of the reactors to prevent air leakage.

RESEARCH REQUIREMENTS

The rate at which tritium oxidizes after release is not known. Research should be performed to assess the current state-of-knowledge of oxidation rates, to determine the additional research requirements, and to supply the missing information. A substantial reduction in estimated doses to nearby persons due to tritium releases would result if it can be shown that tritium does not oxidize rapidly.

Well-developed methods are available for estimating the radiation doses from tritium oxide and radiocarbon releases to persons residing within 50 miles of a radionuclide release point. However, the ability to estimate

doses at greater distances is not as well developed and need improvement in the following areas:

- Estimation of Worldwide Concentrations Due to a Release. Better methods are needed for estimating average regional tritium and radiocarbon concentrations in surface waters and the atmosphere. Current methods use approximate transport and mixing assumptions rather than calculations representative of actual conditions.
- Estimation of U.S. Concentrations Due to a Release. Current methods are regional averaging methods for estimating tritium and radiocarbon concentrations. Methods are needed for estimating the actual plume locations and subsequent dispersion throughout the atmosphere and into the hydrosphere.
- Compilation of World Population Distribution. The current world population data should be converted from a political region basis to a geographical basis corresponding to the geographical regions that would be used in dose calculations.

INTRODUCTION

Radiation doses to an individual and to selected populations from tritium and radiocarbon released to the environment from a fusion power plant were estimated because detailed analysis has shown that these radioisotopes have the highest probability of being released routinely from fusion power plants.

The doses from a release of tritium and radiocarbon at the rate of 1 Ci/yr into the plant gaseous waste stream (stack or vent) and into the liquid waste stream (blowdown pipe) were estimated for a hypothetical maximum individual* who resides near an assumed plant at Morris, Illinois. The doses to the regional population residing within 50 miles of the plant, the population of the eastern U.S., and the world population were also estimated.

TRITIUM DOSES

For the calculation of annual doses to individuals and populations from tritium, dose factors were derived using the method of the ICRP (ICRP, 1959; Soldat, 1971). An average energy for tritium beta particles was taken

*An individual whose place of residence, living, and recreational habits, or dietary habits might result in a higher exposure of radioactive emissions from the plant than a more typical member of the public.

to be 5.7 keV/disintegration (Jacobs, 1968). The effective half-life in the body was assumed to be 10 days (ICRP, 1968) for an adult weighing 70 kilograms (reference man) with a breathing rate of 7300 m^3/yr (ICRP, 1959). The quality factor of 1.7 recommended by the ICRP was used for the dose estimates (ICRP, 1959 and ICRP, 1968).

Adult dose factors (D.F.) for the ingestion and inhalation pathways were derived as the following:

- Ingestion D.F. = 1.02×10^{-7} mrem/yr per pCi/yr intake
- Inhalation D.F. = 7.46×10^{-4} mrem/yr per pCi/m^3 air

To account for the total body dose from the migration of gaseous HTO through the skin (transpiration) the above inhalation dose factor was increased by 50 percent during the dose calculations (Osborne, 1966).

Maximum Individual Dose

For the purpose of estimating the impact of the release of tritiated water (HTO) from the reactor on an individual who may live near the plant, a so-called Maximum Individual was postulated. This person was assumed to:

- Reside 500 meters from the release point at the site boundary on the bank of a river with an average flow of 50,000 cfs where the dilution factor is 0.005 (WASH-1258).
- Drink water drawn from the river near his residence.
- Eat fish and invertebrates (crayfish) caught in the river 100 meters downstream from the plant outfall where the dilution factor is 0.03 (WASH-1258).
- Eat part of his food which was raised under supplemental irrigation through sprinkler systems.

Table 1 summarizes the annual consumption of foods and water intake of this individual along with those for a more average person. The Maximum Individual was assumed to have acquired 50 percent of his milk, vegetables and fruits from outside his farm (noncontaminated); however, 100 percent of

his meat and eggs was assumed produced from locally grown fodder and grain. All of this individual's wheat was assumed grown without irrigation. Annual doses estimated for this Maximum Individual from 1 Ci/yr of tritium released into the liquid effluent* of a fusion reactor are summarized in Table 2.

TABLE 1 Exposure Assumptions Used in Calculating Internal Radiation Doses from a Fusion Reactor

Pathway	Maximum Individual		Population Average		
	Consumption (kg/yr)	Contaminated Fraction(a)	Consumption (kg/yr)	Contaminated Fraction Water	Atmosphere
Ingestion					
Leafy Vegetables	60	0.5	30	0.1	0.5
Other Above Ground Vegetables	63	0.5	23	0.1	0.5
Potatoes	96	0.5	65	0.1	0.5
Root Vegetables	63	0.5	11	0.1	0.5
Berries	26	0.5	3.9	0.1	0.5
Melons	35	0.5	5.2	0.1	0.5
Orchard Fruit	230	0.5	33	0.1	0.5
Wheat	70	0.5(b)	47	0.0	0.5
Other Grain	17	0.5	12	0.1	0.5
Eggs	30	1.0	20	0.1	0.5
Milk	300	0.5	100	0.1	0.5
Beef	40	1.0	40	0.1	0.5
Pork	40	1.0	40	0.1	0.5
Poultry	20	1.0	20	0.1	0.5
Drinking Water	730	1.0	440	0.1	---
Fish	20	1.0	6	0.1	---
Invertebrates	5	1.0	0.5	0.1	---
Inhalation	20 m^3/day	1.0	20 m^3/day	1.0	1.0

(a) For contamination via either irrigation water or atmospheric deposition.
(b) Since wheat is not irrigated, this factor is 0 for surface water release.

*An outfall flow of 50 cfs was assumed.

TABLE 2 Annual Doses to Maximum Individual from Releases of 1 Ci/yr of Tritium to the Atmosphere and to Surface Water (mrem)

	Atmospheric[a]	Surface Water
Inhalation and Transpiration	3.5×10^{-4}	---
Drinking Water[b]	---	8.5×10^{-6}
Aquatic Foods[c]		
Fish	---	1.5×10^{-6}
Invertebrates	---	3.5×10^{-7}
Food Products[b]		
Produce	1×10^{-3}	3×10^{-6}
Milk	2.5×10^{-4}	1.5×10^{-6}
Eggs	2.5×10^{-5}	3.5×10^{-7}
Meat	1×10^{-4}	1×10^{-6}
TOTAL	2×10^{-3}	1.5×10^{-5}

(a) $\bar{\chi}/Q' = 1 \times 10^{-5}$ s/m^3.
(b) Dilution factor = 0.005 at site boundary 500 meters from the outfall.
(c) Dilution factor = 0.03 at 100 meters from the outfall.

The dose to this individual from the gaseous pathways was estimated by assuming he resided all year at the 500-meter location where he consumed food products subject to aerial deposition. The average annual atmospheric dilution factor ($\bar{X}/Q'$) at this location was assumed to be 1×10^{-5} s/m^3 for a 10 meter release height, the value given in WASH-1258 for a typical river site.

The dose from the consumption of food products was estimated by assuming that the foods contained HTO at the same specific activity (T/H ratio) as the water vapor in the air (Baker, et al., 1976) with an absolute humidity of 8 ml/m^3. The food consumption and fraction locally grown are given in Table 1. Dose rates estimated for the individual from a 1 Ci/yr release of HTO into the atmosphere from the fusion reactor (Table 2) also include those from inhalation and transpiration of HTO all year at the 500-meter location.

Population Dose

The radiation doses from HTO released by the fusion reactor were estimated for the population residing at various distances from the facility. As was done for the Maximum Individual, one curie per year was assumed to be released into the air through the plant vent and one curie per year to the river via the blowdown water. The dose to three population groups was estimated:

- Regional population (those persons living within 50 miles of the plant)
- Eastern U.S. population
- World population.

Doses to the above population groups from atmospheric releases of tritium were estimated from environmental concentrations derived from the latitudinal band model of Renne et al. (1975).

Doses to the populations of the eastern U.S. and the world from a release to the surface water were estimated using the model of Easterly, et al. (1974) for world tritium transport. This model divides the world into

hydrological compartments and each reservoir is assumed to be homogenous and any influx of tritium will be instantaneously and completely mixed (within the time step used). The model considers seven compartments or reservoirs: deep ocean, ocean surface, atmosphere, vadose water, ground water, surface water, and man, and the transport rates of tritium in the form of HTO between them. Using Easterly's model and assuming a 1 Ci/yr release to either the atmosphere or surface water compartments for 50 years, the activity in the compartment labeled man, reached equilibrium at 4.5×10^{-7} curies from an atmospheric release and 2.8×10^{-6} curies for the release to surface water.* Thus the release to surface water yielded quantities in man higher by a factor of 6 than the release to the atmosphere.

Annual Dose to Regional Population

The annual dose to those persons living within 50 miles (80 km) of the plant was assumed to be derived from the HTO released into the atmosphere through inhalation and skin absorption, and from the HTO released into the river via drinking water and food products raised with supplementary irrigation. Drinking water and food products were conservatively assumed to contain the same specific activity of tritium as the river water for the liquid release; drinking water and aquatic foods were assumed free of tritium released into the air from the plant.

The distribution of the population (6.4×10^6 persons) was taken from 1970 census data for a plant sited at Morris, Illinois. The contamination fractions used were those given in Table 1. Table 3 summarizes annual doses to the regional population.

Annual Dose to the Eastern U.S. Population

The dose to the population of the eastern U.S. was assumed to be derived from the HTO released into the atmosphere and later washed out into the surface waters by rain. The pathways evaluated were the drinking water and food products in which the specific activity of the tritium was equal

*Unpublished computer program.

to that of the surface waters. The consumption rates used were those of the population average and assuming a contamination fraction of one for all food pathways, 0.5 for drinking water. The inhalation (plus transpiration) dose was estimated for the population of the U.S. living east of the Rocky Mountains using normalized HTO air concentration values derived in Renné, et al. (1975). The dose from a release to surface water was estimated to be be 6 times this on the basis of Easterly's model (Easterly, et al., 1974). Table 4 summarizes the results of the dose calculations. The dose to people living within 50 miles of the plant are not included in the values in this table.

TABLE 3 Annual Doses to Regional Population[(a)] from Releases of 1 Ci/yr of Tritium to the Atmosphere and to Surface Waters (man-rem/yr)

	Atmosphere	Surface Water
Inhalation and Transpiration	3.5×10^{-4}	---
Drinking Water	---	6.5×10^{-4}
Aquatic Foods		
Fish	---	9×10^{-6}
Invertebrates	---	7.5×10^{-7}
Food Products		
Produce	4×10^{-4}	2.5×10^{-4}
Milk	8.5×10^{-5}	1.5×10^{-4}
Eggs	7.5×10^{-6}	3×10^{-5}
Meat	5.5×10^{-5}	1.5×10^{-4}
TOTAL	8.5×10^{-4}	1×10^{-3}

(a) Those persons living within 50 miles of the plant.

TABLE 4 Annual Doses to Eastern U.S. Population[a] from Releases of 1 Ci/yr of Tritium to the Atmosphere and to Surface Water (man-rem/yr)

	Atmosphere	Surface Water
Inhalation and Transpiration	6×10^{-4}	----
Drinking Water	1.5×10^{-3}	
Aquatic Foods		
Fish	4×10^{-5}	
Invertebrates	3.5×10^{-6}	
Food Products		
Produce	1.5×10^{-3}	
Milk	6.5×10^{-4}	
Eggs	1.5×10^{-4}	
Meat	6.5×10^{-4}	
TOTAL	5×10^{-3}	3×10^{-2}[b]

(a) Not including regional population.
(b) Estimated from Easterly's factor of 6 for the surface water/atmosphere dose ratio (Easterly, et al., 1974).

Annual Dose to World Population

The annual dose to the world population from a 1 Ci/yr release to the atmosphere was estimated using the normalized equilibrium surface water concentrations taken from Renné, et al. (1975) and populations (total of 3.8×10^9 people) taken from Machta, et al. (1973). The tritium concentration of the food and water consumed by the people in a latitudinal band was assumed to be the same as that of the surface waters over the land areas of that band. Values of 440 l/yr and 450 kg/yr were taken as the average water and food consumption of the world population, respectively. A

contamination factor of 50 percent was used for the drinking water, since water drawn from deep wells would probably not be contaminated with HTO released from the fusion reactor. Table 5 summarizes the annual doses to the world population derived from the atmospheric release of HTO, and the total estimated dose from a surface water release by the use of the factor of 6 suggested by Easterly, et al. (1974).

TABLE 5 Annual Doses to World Population from Releases of Tritium to Atmosphere and Surface Water (man-rem/yr)

	Atmosphere	Surface Water
Inhalation and Transpiration	7×10^{-4}	
Drinking Water	1.5×10^{-3}	
All Foods	2.5×10^{-3}	
TOTAL	5×10^{-3}	3×10^{-2}(a)

(a) The dose from releases of HTO to surface water has been estimated at about 6 times that from release to the atmosphere using the model suggested by Easterly.

Summary of Dose to the Population Group from Tritium

The annual doses to the population from releases of tritium to the atmosphere and surface water are summarized in Table 6.

TABLE 6 Summary of Annual Doses to Populations from Releases of 1 Ci/yr Tritium (HTO) to the Atmosphere and Surface Water (man-rem)

	Atmosphere Release	Surface Water Release
Regional	8.5×10^{-4}	1×10^{-3}
United States	5×10^{-3}	3×10^{-2}
World(a)	5×10^{-3}	3×10^{-2}
TOTAL (Earth)	1×10^{-2}	6×10^{-2}

(a) The world dose includes that dose to the U.S. population using the latitudinal band model.

Comparison of HTO World Population Dose with EPA Model

The EPA model given in reference (EPA, 1974) assumes that the tritium released from a plant in the continental U.S. is transported eventually to the world's oceans to be mixed uniformly in only that portion in the northern hemisphere. Only the population of the northern hemisphere (80% of the world population) is assumed effected such that their body water would be at the same specific activity as the northern hemisphere oceans at equilibrium after a constant release rate of tritium into these waters. If the volume of water is taken to be 7×10^{15} m^3 (EPA, 1974); the world population is 4×10^9 people; and the total-body dose factor for sustained concentration is 100 rad/yr per Ci/m^3 (EPA, 1974) of tritium in the body, then the annual world dose from an annual release of 1 Ci of tritium in the form of HTO after equilibrium is just

$$\frac{1 \text{ Ci/yr}}{7 \times 10^{15} \text{ m}^3} \times 0.8 \times 4 \times 10^9 \text{ people} \times 100 \frac{\text{rad/yr}}{\text{Ci/m}^3} \times \frac{12.3 \text{ yr}}{\ln 2} = 8 \times 10^{-4} \text{ man-rad/yr}$$

or a dose equivalent of

$$1.5 \times 10^{-3} \text{ man-rem/yr}$$

From Table 6, an atmospheric release of 1 Ci/yr of HTO was estimated to give a dose 5×10^{-3} man-rem/yr to the world population. This estimate is about 3 1/2 times that of the EPA.

CARBON-14 DOSES

Fusion power plants may release carbon-14 to the atmosphere from their gas separation systems (Kaser, 1976). Since this radiocarbon may reach man by various pathways and since carbon is a major constituent of the body, doses from this radionuclide were estimated using the specific activity method.

Maximum Individual Dose

First year doses were estimated from inhalation and air submersion to the maximum individual residing 500 meters from the plant and from eating foods grown at this location. For this dose estimate it was assumed that the specific activity of the carbon-14 in the contaminated foods was the same as that of the air; i.e., the ratio of carbon-14 to total carbon in the foods is equal to the ratio in the atmosphere (Baker, et al., 1976). The natural concentration value of CO_2 in the atmosphere was taken to be 320 parts per million (Machta, 1973). The value of 0.23 was taken for the fraction of carbon in the body of the Reference Man (ICRP-23, 1974). The average energy of the carbon-14 beta particle was taken to be 0.054 MeV for total body and 0.27 MeV for bone (ICRP-10, 1968). The food consumption rates and contamination factors were given in Table 1.

Dose factors used for estimates were taken from Soldat, et al. (1973 and 1974). The 50-year dose commitment is essentially the same (less than 20% greater) as the first year dose since the effective half-life in the body is short (10 days for total body to 40 days for bone). Table 7 lists the amount released and the first year doses to the maximum individual for the organs of importance.

TABLE 7 First Year Dose (mrem) to Maximum Individual from 1 Ci/yr Carbon-14 Released into the Atmosphere

External[a]	Skin	Total Body	Bone
Air Submersion	1×10^{-5}	4×10^{-8}	---
Internal[b]			
Inhalation	---	9.5×10^{-4}	4.5×10^{-3}
Food Products	---	0.09	0.4
TOTAL	1×10^{-5}	0.09	0.4

(a) Continuously exposed at 500 meters from plant. No credit for shielding by structures.
(b) 50-year dose commitments are less than 20% more than the first year dose.

Population Dose

The carbon-14 total-body dose to the population groups living in three regions was estimated:

- Within the 50-mile radius of the plant
- In the eastern U.S.
- In the world

The normalized air concentrations for HTO given in Renné, (1975) were assumed to be valid for the carbon-14 dispersed in the atmosphere. The specific activity of the carbon-14 in the bodies of the population groups was assumed equal to the specific activity of the carbon-14 in the atmosphere. Table 8 summarizes the doses from carbon-14 to the population groups. The persistence of carbon-14 in the environment leads to the conclusion that extensive effort is justified for preventing releases of carbon-14. Double containmment, for example, should prevent leakage of air into the reactors and the formation of carbon-14 when nitrogen absorbs neutrons.

TABLE 8 First Year Total-Body Dose to the Population Groups from 1 Ci/yr of Carbon-14 Released into the Atmosphere

Population Group[a]	Dose(man-rem)[b]
Regional	0.45
Eastern U.S.[c]	0.75
World	0.9
TOTAL	2

(a) Populations used were referenced in Renné, 1975.
(b) 50-year dose commitments are essentially the same as the first year dose.
(c) Other than population living within 50 miles.

FUTURE RESEARCH NEEDS

The uncertainties and omissions in the above analysis of the population radiation doses are manifold. One critical item that needs to be improved is the estimation of the world-wide HTO and radiocarbon concentrations in surface waters and atmosphere from a release to the surface water. Thus study is pivotal in the determination of how best to release tritium

and radiocarbons with the least environmental detriment into atmosphere or surface water. Further study is necessary to describe the movement and subsequent accumulation of tritium in the form of tritiated water throughout the reservoirs of the world for a continuous or instantaneous release from a fusion power plant into the surface water as well as the atmosphere.

Another important deficiency is the lack of information on the conversion of tritium to tritium oxide in the atmosphere. At present, dose calculations assume instantaneous conversion to the oxide with the result that estimated nearby radiation doses are higher by as much as a factor of 1000 than the estimated doses if the tritium remained unoxidized. A state-of-the-art document describing the current information and research needed to define the actual oxidation rate should be written and that research should be completed. A significant reduction in the estimated tritium radiation doses could result.

Other research needs are:

- A better model for the determination of atmospheric concentrations over the continental United States from a release anywhere in the U.S. Possibly this model could include a puff advection methodology as advanced by Wendell (Start and Wendell, 1974). Using the model, comparisons could be made of the variation of population dose with site.
- A comprehensive enumeration of the world population into geographic areas--not political areas. These areas could be 10 degrees on a side and coincide with the standard latitude and longitude grid.

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