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Abstract

Radionuclide inventories have been estimated for the reactor cores, reactor components, and primary system corrosion products in the former Soviet Union naval reactors dumped at the Abrosimov Inlet, Tsivolka Inlet, Stepovoy Inlet, Techeniye Inlet, and Novaya Zemlya Depression sites in the Kara Sea between 1965 and 1988. For the time of disposal, the inventories are estimated at 17 to 66 kCi of actinides plus daughters and 1,695 to 4,782 kCi of fission products in the reactor cores, 917 to 1,127 kCi of activation products in the reactor components, and 1.4 to 1.6 kCi of activation products in the primary system corrosion products. At the present time, the inventories are estimated to have decreased to 6 to 24 kCi of actinides plus daughters and 492 to 540 kCi of fission products in the reactor cores, 124 to 126 kCi of activation products in the reactor components, and 0.16 to 0.17 kCi of activation products in the primary system corrosion products. All actinide activities are estimated to be within a factor of two.

We have also conducted a preliminary risk assessment of key actinides and fission products in the discarded spent nuclear fuel as a means of identifying which radionuclides are most important from a human-health standpoint. Results of such an assessment can also be used to guide future monitoring programs conducted in Arctic waters. Global population doses resulting from the release of radionuclides contained in the reactors were estimated using simple dose-conversion factors (developed originally by UNSCEAR) that provide estimates of collective dose commitments for unit releases of radionuclides to sea water. The estimated population doses using the appropriate dose conversion factors and the estimated inventories are 2.3 person-Sv for ^{90}Sr, 4.2 person-Sv for ^{241}Am, 5.2 person-Sv for ^{137}Cs, and 0.1 person-Sv for ^{239}Pu. One interesting result is that although the inventory of ^{241}Am is much lower than the inventory of ^{90}Sr, ^{241}Am has a greater predicted collective dose commitment because of a higher dose-conversion factor. Finally, based on a cancer-risk factor of 0.05/Sv, we calculate a global risk of 0.6 fatal cancers for release of the key actinides and fission products. By comparison, the population risk for the Chernobyl accident has been estimated to be 17,000 fatal cancers.

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Introduction

In the Spring of 1993, a Russian report, "Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation,"[1] was released. The findings presented in this Russian report were the result of a scientific study commissioned by the Office of the President of the Russian Federation and headed by Dr. Alexi V. Yablokov. The Yablokov Commission, as they were later called, reported that 16 naval reactors from seven former Soviet Union submarines and the icebreaker *Lenin*, each of which suffered some form of reactor accident, were dumped at five sites in the Kara Sea. Six of these 16 naval reactors contained their spent nuclear fuel (SNF). In addition, approximately 60% of the SNF from the three *Lenin* naval reactors was disposed of in a reinforced concrete container and metal shell. The Yablokov Commission estimates of radioactivity were limited to the fission products in the SNF and the ^{60}Co in the reactor components, both at the time of disposal. With rare exception, specific radionuclides were not identified and there was no estimate provided for the current levels of radioactivity.

Without a knowledge of the specific radionuclides and their current levels of radioactivity, the health risks to man from these 16 former Soviet Union naval reactors and their SNF are difficult to predict. This report presents the results of an independent effort to provide the necessary time-dependent inventory of the radionuclides.

Background Information

The information presented herein highlights the conclusions of the Yablokov Commission and what we know or have assumed about the history of each submarine. Table 1 presents the Yablokov Commission findings for the five Kara Sea disposal sites.[1] Summarized for each disposal site is the disposal date, the number of discarded naval reactors and their associated ship identification number, the number of discarded naval reactors containing SNF, and the estimated fission product radioactivity in the SNF at the time of disposal. The Tsivolka Inlet entries are for the three naval reactors from the icebreaker *Lenin* and the reinforced concrete container and metal shell containing approximately 60% of her SNF (1.7 reactor cores) that were discarded in 1967. The 100 kCi reported for the *Lenin* disposal result primarily from the fission products ^{90}Sr and ^{137}Cs. The two naval reactors containing SNF that were discarded in the Stepovoy inlet in 1981 are identified as being of a liquid metal cooled type. The Yablokov Commission estimates of total radioactivity are 2,300 kCi of fission products in the SNF and 100 kCi of ^{60}Co in the reactor components. No information was provided which would allow association of a given ship identification number with a specific submarine class or accident date.

To estimate the time-dependent inventory of radionuclides in the discarded naval reactors, reactor core operating histories and the accident date associated with each discarded naval reactor are required. Unfortunately, reactor core histories for the seven former Soviet Union submarines were not available. Therefore, an analytical model was developed to estimate the minimum reactor fuel load for each submarine whose discarded naval reactors contained

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SNF. As will be discussed later, the model uses as its basis Western estimates of the shaft horsepower of each submarine involved. Selection of an appropriate shaft horsepower requires a knowledge of each submarine's NATO classification.

Table 2 presents a summary of the Western estimates of the identities of the submarines whose naval reactors were dumped in the Kara Sea.[2,3] Summarized for each submarine is the K identification number, NATO classification, and associated reactor accident date. The two naval reactors in the K-27 are reported to have been of a liquid metal type.[2] All other discarded naval reactors are believed to have been of the pressurized water reactor (PWR) type.[4] Three of these submarines, K-3, K-11, and K-19, were observed in active service some years after suffering their reactor accidents. While each of the seven identified submarines was reported to have suffered some form of reactor accident, none was reported to have sunk.

With the information of Table 2 as a basis, a NATO classification was assigned to the ship identification of each submarine whose discarded naval reactors contained SNF. Table 3 presents a summary of our deductions. Summarized for each disposal date is the number of discarded naval reactors containing SNF and associated ship identification number, the K identification number, and the NATO classification. The rationale for our selections was as follows. A recent International Atomic Energy Agency publication[3] identifies three of the four submarines whose naval reactors were discarded in 1965 and 1966 as the K-3, K-11, and K-19. In addition, the submarine whose two naval reactors were discarded in 1981 is identified as the K-27. Since the Yablokov Commission report specified that the minimum time period between reactor shutdown and disposal was one year, we believe that the two submarines associated with the three naval reactors containing SNF that were discarded in 1965 are the K-3 and K-19. Since the first K-3 submarine reactor accident involved no fatalities and she was observed in active service some years later,[2] one may infer that while both naval reactors were undoubtedly replaced, only one of the two discarded naval reactors contained SNF. Furthermore, since the K-19 submarine reactor accident involved fatalities, the accident was of such severity that she was nicknamed "Hiroshima," and she was observed in active service some years later,[2] one may infer that both naval reactors were removed and that each contained SNF. Thus, the K-3 was assigned to the ship identified as No. 285, and the K-19 was assigned to the ship identified as No. 901. Through a similar process of elimination, the submarine associated with the one naval reactor containing SNF that was discarded in 1972 was assigned to the K-140. The three remaining submarines, K-5, K-11, and K-22, are assumed to be associated with discarded naval reactors without SNF.

Analytical Model

The information presented herein describes (1) the analytical model used to estimate the minimum reactor fuel load for each submarine whose discarded naval reactors contained SNF, (2) the information that we know or have assumed about the operating characteristics of the icebreaker *Lenin* and each submarine whose discarded naval reactors contained SNF, and (3) the method used to predict the activation product inventories in the reactor components and primary system corrosion products of all discarded naval reactors.

With an estimate of the reactor fuel load, the reactor power, and the reactor operating history, one can proceed to calculate the radionuclide inventory associated with the SNF. Before describing the computer code that was used to estimate the inventory, the information that is required as input must be addressed. In the case of the icebreaker *Lenin*, core history information necessary to the inventory calculations was directly available from Russian sources.[5,6] Table 4 presents a summary of the naval reactor core information for the icebreaker *Lenin*. Summarized for each of the three *Lenin* reactors is the ^{235}U loading, the operating period, and the number of effective full power hours. From the information contained in Table 4, the average full power of each reactor is calculated to be 65 megawatts thermal (MW). The three *Lenin* reactors were reported to contain a total of 219 fuel assemblies with a ^{235}U enrichment in the range of 4.6 to 6.4%. The reactor accident that precipitated the need for disposal of the three naval reactors and a portion of their fuel occurred either early or late in the year of 1966, some three years after the reactors were refueled. The Yablokov Commission report states that SNF from 125 fuel assemblies, or approximately 60% of the three reactor cores, was discarded. The total number of fuel assemblies that this 60% finding implies is on the order of 208, which is in excellent agreement with the 219 fuel assemblies previously reported for the *Lenin*. As such, added credence is given to the *Lenin* core history information.

For national security assets such as nuclear powered submarines, core history information like that published on the *Lenin* is virtually impossible to obtain. As such, a method for estimating the necessary reactor fuel load had to be developed. Assuming one knows the operating characteristics of the submarine, estimates of the reactor fuel load can be made from the power requirements of the submarine. For a submarine to operate at a given speed, S_i, the power requirement, P_i, in MW, is given by:

$$P_i = (SHP)\,(CF_1)\,(S_i/S_{max})^3$$

where
SHP = shaft horsepower, hp, and
CF_1 = 0.7457×10^{-3} MW/hp.

The overall power requirement of the reactor, P_R, in MW, is given by:

$$P_R = [(P_i/PE) + HL]/N_R$$

where
PE = propulsion efficiency,
HL = "hotel" load requirements, MW, and
N_R = numbers of reactors.

The propulsion efficiency is that of the plant, and includes both thermal and mechanical conversion. The "hotel" load represents the total thermal power requirements of the submarine for all electric power and steam loads.

The minimum quantity of ^{235}U required to power the submarine for a specific duration, $^{235}UL_{min}$, in grams, is given by:

$$^{235}UL_{min} = (CF_2)\,(P_R)\,(AST)\,(CL)$$

where
CF_2 = 1.24 grams ^{235}U/MWd,
AST = at-sea time, d/y, and
CL = core life, y.

The minimum quantity of U in the submarine reactor fuel load, UL_{min}, in grams, is given by:

$$UL_{min} = {}^{235}UL_{min}/E_U$$

where
E_U = enrichment of ^{235}U.

Note that the minimum quantity of U in the reactor fuel load, UL_{min}, is not the amount that is actually predicted to be loaded in the submarine, but rather the minimum quantity of U required for the submarine to operate at speed S_i for a time period equal to the product of the at-sea time and core life. A substantially greater amount of U would be required for a full reactor load.

Table 5 presents a summary of the basic data used to estimate the minimum quantity of U in the reactor fuel load for each submarine whose discarded naval reactors contained SNF. Summarized for each of the various parameters is the range of values and the value assumed. The average speed at which each submarine was assumed to operate was arbitrarily set at 11 knots. For the shaft horsepower and maximum speed of the submarines, the average of the range of values was assumed. In the case of the propulsion efficiency, hotel load, at-sea time, and core life, the value assumed was the range limit or value that would maximize the minimum quantity of U in the reactor fuel load. The value limits on enrichment are a best estimate from the available data. While the lower range limit is considered nominal for first-generation submarines of the November and Hotel class, the inclusion of a Yankee II class submarine requires the assumption of a range in enrichment.

The radionuclide inventory in the SNF of the discarded naval reactors was calculated with ORIGEN2,[13] a point (no spatial dependence) depletion personal computer code that has been used extensively to characterize spent nuclear fuel and high level waste. The ORIGEN2 fixed data library used in these estimates is that for a generic PWR fueled with UO_2 enriched to 4.2% in ^{235}U at a burnup of 50,000 MW days per metric tonne of U. A number of factors were considered in the selection of this particular library. First, 14 of the 16 discarded naval reactors are believed to be of the PWR type. Second, since the *Lenin* fuel matrix was described in the Yablokov Commission report as UO_2, it follows that the fuel matrix in first-generation submarine naval reactors built during the same period of time was also very likely UO_2. Third, the lowest ^{235}U enrichment in the *Lenin* reactors was quite close to 4.2%.

The highest ^{235}U enrichment considered for the former Soviet Union submarines is substantially greater than 4.2%. One might expect that as the ^{235}U enrichment is increased, there will be a proportional decrease in the production of actinides. This is not the case; as the ^{235}U enrichment is increased, the neutron energy spectrum can be expected to harden or shift toward higher energies. With this shift in neutron spectrum, more resonance absorptions are expected to occur, which, in turn, will lead to a relative increase in the production of actinides. For a ^{235}U enrichment of 36%, the use of ORIGEN2 may result in an underestimate of the actinides by as much as a factor of two. The effect of a ^{235}U enrichment of 36% on the ORIGEN2 fission product estimate is believed to be significantly less. A more accurate estimate of the actinides in the higher enrichment fuels may be calculated with the computer code ORIGEN-S.[14] However, to perform this calculation, one must know either the relative shape and magnitude of the neutron energy spectrum or the composition and dimensions of a reactor fuel assembly or unit cell. Since information such as this was not readily available, the limitation in the prediction of the actinide inventory associated with the use of ORIGEN2 was considered acceptable.

To predict the activation product inventories in the reactor components and primary system corrosion products of the discarded naval reactors, the results of a British calculation for a generic nuclear powered submarine one year after shutdown were used.[15,16] Table 6 presents a summary of the British results. Summarized for each of the selected activation products are the radionuclide half-life, reactor component radioactivity, and primary system corrosion product radioactivity. Since the reactor power level of a typical first-generation British submarine is similar to Western estimates of the reactor power levels of the discarded naval reactors, it follows that the data of Table 6 may be used without exception. For the reactor components the estimated total radioactivity is 79,100 Ci, with ^{55}Fe, ^{60}Co, and ^{63}Ni as the most dominant radionuclides, respectively. For the primary system corrosion products, the estimated total radioactivity is reduced to 111 Ci, with ^{60}Co as the most dominant.

Characteristics of Selected Radionuclides

The inventory of radionuclides in this estimate is limited in scope. For the most part, the inventory consists of radionuclides with long half-lives or which are of concern as ingestion products, the most likely pathway of dose to man. Table 7 presents a summary of the characteristics of the selected actinide, fission product, and activation product radionuclides in the inventory. Summarized for each selected radionuclide is the radionuclide half-life, type of radiation emitted, average energy associated with each radiation type, and the annual limit on intake for ingestion. The annual limit of intake for ingestion represents the quantity of a given radionuclide that, when ingested over a period of one year, will result in a dose of 5 rem. For simplicity, the radionuclides of a given type - actinide, fission product, or activation product - have been arranged in order of decreasing toxicity. With the exception of ^{241}Pu, the actinides are the most toxic of the selected radionuclides in the inventory. The toxicity of ^{241}Pu is greater than that of ^{134}Cs and less than that of ^{90}Sr. With the exceptions of ^{60}Co and ^{14}C, the activation products are the least toxic of the selected radionuclides in the inventory. The toxicity of ^{60}Co is greater than that of ^{154}Eu and less than that of ^{137}Cs. The toxicity of ^{14}C is equivalent to that of ^{125}Sb.

Results

The estimated inventory of radionuclides presented herein was developed through an assessment of the variability of two key parameters: ^{235}U enrichment and time between reactor shutdown and disposal of the SNF. The effect of ^{235}U enrichment on the estimated inventory of radionuclides was evaluated for the *Lenin* and submarine naval reactors in the following way. In the case of the three *Lenin* naval reactors, the reported range in ^{235}U enrichment was assumed to be associated with a single three-reactor core load. Under a further assumption that the three *Lenin* reactors were loaded with approximately equal quantities of U, the ^{235}U enrichments of 4.6% and 6.4% were associated with the two reactors loaded with 76 and 80 kg of ^{235}U and the one reactor loaded with 129 kg of ^{235}U, respectively. In the case of the six submarine naval reactors containing SNF, the assumed minimum and maximum in ^{235}U enrichment were associated with separate reactor core loads.

The effect of time between reactor shutdown and disposal, or decay time, on the estimated inventory of radionuclides was evaluated by assuming a minimum decay time and a best estimate decay time for each navel reactor and disposal site. By definition, the minimum decay time for each naval reactor was chosen such that the estimate of the inventory of radionuclides at the time of disposal would be a maximum, and the best estimate decay time for each naval reactor was chosen such that a more realistic estimate of the inventory of radionuclides at the time of disposal would result. Table 8 presents a summary of the assumed time periods between reactor shutdown and disposal for the naval reactors dumped in the Kara Sea. Summarized for each disposal site is the disposal date, the number of discarded naval reactors and their associated ship identification number, the minimum decay time, and the best estimate decay time. With the exception of the two naval reactors that were discarded in Stepovoy Inlet in 1981, the minimum decay times were based on the Yablokov Commission finding of a minimum period of one year between reactor shutdown and disposal. The two naval reactors discarded in Stepovoy Inlet were earlier identified with the K-27, an assumed November class submarine that suffered a reactor accident on May 24, 1968. As such their minimum decay time was established at thirteen years.

The best estimate decay time for each submarine whose discarded naval reactors contained SNF was assumed to be the time period, in whole years, between their associated accident and disposal dates. For those submarines whose discarded naval reactors are without SNF, the best estimate decay time was arbitrarily established at one year. In the case of the *Lenin*, whose reactor accident was reported to have occurred either early or late in 1966, the best estimate decay time was established at two years.

Table 9 presents a summary of the estimated activity in the SNF at the time of disposal. Summarized for each of the selected actinides and fission products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the selected actinides, the radionuclide and disposal site with the greatest activity are ^{241}Pu and Tsivolka Inlet, the location of the *Lenin* remnants, respectively. With respect to the selected fission products, the radionuclides with greatest activity are ^{147}Pm, ^{137}Cs, and ^{90}Sr, respectively. The disposal sites with greatest total activity are Tsivolka Inlet and Abrosimov Inlet, respectively. Overall, for the time of disposal, the inventories are estimated at 69 to 111 kCi of actinides plus daughters and 3,053 to 7,472 kCi of fission products. The later range in activity compares favorably with the Yablokov Commission finding of 2,300 kCi of fission products.

Table 10 presents a summary of the estimated radioactivity for selected activation products in reactor components and primary system corrosion products at the time of disposal. Summarized for each of the selected activation products are the minimum and maximum in radioactivity associated with the five disposal sites in the Kara Sea. With respect to the reactor components, the radionuclide and disposal site with greatest activity are ^{55}Fe and Abrosimov Inlet, respectively. Since the radioactivity in the reactor components and primary system corrosion products at a given disposal site is simply a function of the number of reactors discarded, Abrosimov Inlet is the expected site of greatest activity. Overall, for the time of disposal, the inventories are estimated at 917 to 1,127 kCi of activation products in the reactor components and 1.4 to 1.6 kCi of activation products in the primary system corrosion products. Of the 917 to 1,127 kCi of activation products in the reactor components, 161 to 184 kCi are associated with the ^{60}Co inventory in the sixteen discarded naval reactors. On a per-reactor basis, the estimated ^{60}Co inventory in the reactor components is in excellent agreement with the Yablokov Commission finding of 100 kCi in the reactor components of ten naval reactors.

Table 11 presents a summary of the estimated radioactivity in the SNF at the present time (1993). Summarized for each of the selected actinides and fission products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the selected actinides, the radionuclide and disposal site with the greatest activity remain ^{241}Pu and Tsivolka Inlet, respectively. With respect to the selected fission products, the radionuclides with greatest activity are now ^{137}Cs and ^{90}Sr, respectively. The disposal sites with greatest total activity remain Tsivolka Inlet and Abrosimov Inlet, respectively. Overall, for the present time (1993), the inventories are estimated at 23 to 38 kCi of actinides plus daughters and 674 to 708 kCi of fission products.

Table 12 presents a summary of the estimated radioactivity for selected activation products in reactor components and primary system corrosion products at the present time (1993). Summarized for each of the selected activation products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the reactor components, the radionuclides with greatest activity are ^{63}Ni at Abrosimov Inlet and ^{55}Fe at Techeniye Inlet, while the disposal site of greatest activity is now Techeniye Inlet. With respect to the primary system corrosion products, the radionuclide and disposal site with greatest activity are ^{60}Co and Techeniye Inlet, respectively. That Abrosimov Inlet is no longer the site of greatest activity is not surprising. While the radioactivity in the reactor components and primary system corrosion products at a given disposal site remains a simple function of the number of reactors discarded, when radioactive decay of the activation products is considered, Techeniye Inlet becomes the expected site of greatest activity. Overall, for the present time (1993), the inventories are estimated at 125 to 126 kCi of activation products in the reactor components and 0.16 to 0.17 kCi of activation products in the primary system corrosion products.

Table 13 presents a summary of the estimated radioactivity in the SNF at twenty years hence (2013). Summarized for each of the selected actinides and fission products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the selected actinides, the radionuclide and disposal site with the greatest activity remain ^{241}Pu and Tsivolka Inlet, respectively. With respect to the selected fission products, the radionuclides with greatest activity remain ^{137}Cs and ^{90}Sr, respectively. The disposal sites with greatest total activity remain Tsivolka Inlet and Abrosimov Inlet, respectively. Overall, for twenty years hence (2013), the inventories are estimated at 11 to 18 kCi of actinides plus daughters and 415 to 437 kCi of fission products.

Table 14 presents a summary of the estimated radioactivity for selected activation products in reactor components and primary system corrosion products at twenty years hence (2013). Summarized for each of the selected activation products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the reactor components, the radionuclide with the greatest activity remains ^{63}Ni, while the disposal site of greatest activity is once again Abrosimov Inlet. With respect to the primary system corrosion products, the radionuclide and disposal site with greatest activity remain ^{60}Co and Techeniye Inlet, respectively. That Abrosimov Inlet and Techeniye Inlet are now the sites of greatest activity for the reactor components and primary system corrosion products, respectively, is not surprising. While the radioactivity in the reactor components and primary system corrosion products at a given disposal site remains a simple function of the number of reactors discarded, when radioactive decay of the activation products is considered, both Abrosimov Inlet and Techeniye Inlet become the expected sites of greatest activity. Overall, for twenty years hence (2013), the inventories are estimated at 63.5 to 64 kCi of activation products in the reactor components and 0.014 to 0.015 kCi of activation products in the primary system corrosion products.

The figures that follow depict the inventories of selected radionuclides as a function of time. The time period of interest is that from the date of first disposal to the present time (1993). In preparing these graphical presentations of the time-dependent radionuclide inventory estimates, the following convention was adopted.

Reactor cores:

○ = Submarine reactors at 10% ^{235}U - minimum decay time
● = Submarine reactors at 36% ^{235}U - minimum decay time
□ = Submarine reactors at 10% ^{235}U - best estimate decay time
■ = Submarine reactors at 36% ^{235}U - best estimate decay time

Reactor components:

▼ = Minimum decay time
▲ = Best estimate decay time

Figures 1 - 4 depict the results of the activity estimates for selected actinides in the discarded naval reactors containing SNF. Figures 5 - 14 depict the results of the activity estimates for selected fission products in the discarded naval reactors containing SNF. Activity estimates for selected activation products in the reactor components are depicted in Figures 15 - 19. Total activity estimates for the actinides, fission products, and activation products in the reactor components are depicted in Figures 20 - 22, respectively.

Conclusions

Considering the uncertainties associated with certain of the analytical model parameters and in the times between reactor shutdown and disposal, the estimates presented herein agree quite favorably with the Yablokov findings for the time of disposal.

At the present time (1993), even if one assumes that the actinides are underestimated by a factor of two, the inventories of actinides and fission products in the SNF and the inventories of activation products in reactor components and primary system corrosion products are estimated to be no greater than 76 kCi, 708 kCi, 126 kCi, and 0.17 kCi, respectively. Total inventory is estimated at less than 911 kCi.

At twenty years hence (2013), even if one continues to assume that the actinides are underestimated by a factor of two, the inventories of actinides and fission products in the SNF and the inventories of and activation products in reactor components and primary system corrosion products are estimated to be no greater than 36 kCi, 437 kCi, 64 kCi and 0.015 kCi, respectively. Total inventory is estimated at less than 538 kCi.

Based upon the estimated inventory of radionuclides, Tsivolka Inlet, the location of the *Lenin* remnants, and Abrosimov Inlet remain the disposal sites with the greatest total activity, respectively.

Recommendations

Improvements may be made in the calculation of the estimated inventory of radionuclides. To achieve the improvements desired, the following steps are recommended: (1) obtain definitive information on the time period between the shutdown date of each reactor and the date of its disposal, (2) validate the core histories of all discarded naval reactors containing SNF, (3) obtain definitive information on the materials of construction and geometry of a typical fuel assembly, and (4) obtain definitive information on the neutron energy spectrum in the reactors involved.

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Table 1. Yablokov Commission findings for the former Soviet Union naval reactors dumped in the Kara Sea.[1]

Disposal Site	Disposal Date	Naval Reactors Discarded	Reactors Containing SNF	Fission Product Activity (kCi)
Abrosimov Inlet	1965	2 (No. 285)	1	800
		2 (No. 901)	2	400
		2 (No. 254)	-	-
	1966	2 (No. 260)	-	-
Tsivolka Inlet	1967	3 (OK-150)	1.7*	100
Novaya Zemlya Depression	1972	1 (No. 421)	1	800
Stepovoy Inlet	1981	2 (No. 601)	2	200
Techeniye Inlet	1988	2 (No. 538)	-	-
Total		16	7.7	2,300

*The SNF was not contained in the naval reactors, but in a reinforced concrete and metal shell.

Table 2. Western estimates of the identities of the former Soviet Union submarines whose naval reactors were dumped in the Kara Sea.[2,3]

Submarine Identification	NATO Classification	Reactor Accident Date
K-3	November	June, 1962 September 8, 1967
K-5	Hotel/November	Mid-1960s
K-11	November	February 12, 1965
K-19	Hotel	July 4, 1961
K-22*	--	--
K-27	November	May 24, 1968
K-140	Yankee II	August 23, 1968

*No information is currently available in the open literature for this submarine.

Table 3. Best estimate association of ship identification with the NATO classification of each submarine whose discarded naval reactors contained SNF.

Disposal Date	Reactors Containing SNF	Submarine Identification	NATO Classification
1965	1 (No. 285)	K-3	November
	2 (No. 901)	K-19	Hotel
1972	1 (No. 421)	K-140	Yankee II
1981	2 (No. 601)	K-27	November

le 4. Naval reactor core information for the former Soviet Union icebreaker *Lenin*.[5,6]

Total number of assemblies: 219 ^{235}U enrichment range: 4.6% to 6.4%

	Core Histories		
al Reactor	^{235}U Loading (kg)	Operating Period (MW hours)	Effective Full Power Hours (hours)
1	80	560,000	8,600
2	76	550,000	8,500
3	129	660,000	10,000

Table 5. Summary of the basic data used to estimate the minimum quantity of U in the reactor fuel load for each former Soviet Union submarine whose discarded naval reactors contained SNF.

Parameter	Value Range	Value Assumed
November class SHP (10^3hp)[7,8]	30.0 - 35.0	32.5
Hotel class SHP (10^3hp)[8,9]	29.5 - 30.0	29.75
Yankee II class SHP (10^3hp)[7,8,10]	29.5 - 45.0	37.25
November class S_{max} (knots) [7,8]	28 - 30	29
Hotel class S_{max} (knots) [8,9]	23 - 26	24.5
Yankee II class S_{max} (knots) [7,8,10]	26.5 - 27	26.75
Propulsion efficiency, PE, (%)[11]	15 - 20	15
Hotel load, HL, (MW)	12 - 15	15
Number of reactors, N_R [8,9,10]	2	2
At-sea time, AST (d/y)	120	120
Core life, CL, (y)	5 - 7	7
^{235}U enrichment, E_U, (%) [12]	10 - 36	10 - 36

Table 6. Information used to predict the radionuclide inventory in the reactor components and primary system corrosion products in the former Soviet Union naval reactors dumped in the Kara Sea.[15,16]

		Activity (Ci)	
Nuclide	Half-life (y)	Reactor Components	Primary System Corrosion Products
^{60}Co	5.27	1.27×10^{4}	1.09×10^{2}
^{14}C	5,730	1.14×10^{1}	1.57×10^{-5}
^{63}Ni	100.1	5.22×10^{3}	2.61×10^{-1}
^{55}Fe	2.73	6.11×10^{4}	1.94×10^{0}
^{59}Ni	75,000	4.68×10^{1}	1.37×10^{-3}
Total		7.91×10^{4}	1.11×10^{2}

Table 7. Characteristics of the selected actinide, fission product, and activation product radionuclides in the inventory.

Nuclide	Half-Life (y)	Radiation Type	Average Energy (MeV)	Annual Limit on Intake[17] (μCi)
Actinides				
^{239}Pu	24,110	α	5.10	0.8
^{240}Pu	6,563	α	5.16	0.8
^{241}Am	432.7	α	5.48	0.8
		β	0.0304	
		γ	0.0287	
^{238}Pu	87.7	α	5.49	0.9
		γ	0.0992	
		β	0.00176	
^{241}Pu	14.4	β	0.00520	40
		α	0.00012	
Fission Products				
^{129}I	15,700,000	β	0.0556	5
		γ	0.0248	
^{90}Sr	28.5	β	0.196	30
^{134}Cs	2.06	γ	1.55	70
		β	0.164	
^{137}Cs	30.0	γ	0.566	100
		β	0.25	
^{154}Eu	8.8	γ	1.25	500
		β	0.279	
^{125}Sb	2.73	γ	0.443	2,000
		β	0.126	
^{147}Pm	2.62	β	0.062	4,000
^{155}Eu	4.96	β	0.065	4,000
		γ	0.063	
^{99}Tc	213,000	β	0.085	4,000
^{151}Sm	90	β	0.125	10,000
Activation Products				
^{60}Co	5.27	γ	2.50	200
		β	0.0960	
^{14}C	5,730	β	0.0495	2,000
^{63}Ni	100.1	β	0.0171	9,000
^{55}Fe	2.73	β	0.0038	9,000
		γ	0.0016	
^{59}Ni	75,000	β	0.0041	20,000
		γ	0.0026	

Table 8. Assumed time periods between reactor shutdown and disposal for the former Soviet Union naval reactors dumped in the Kara Sea.

Disposal Site	Disposal Date	Naval Reactors Discarded	Minimum Decay Time (y)	Best Estimate Decay Time (y)
Abrosimov Inlet	1965	2 (No. 285)	1.0	3.0
		2 (No. 901)	1.0	4.0
		2 (No. 254)	1.0	1.0
	1966	2 (No. 260)	1.0	1.0
Tsivolka Inlet	1967	3 (OK-150)	1.0	2.0
Novaya Zemlya Depression	1972	1 (No. 421)	1.0	4.0
Stepovoy Inlet	1981	2 (No. 601)	13.0	13.0
Techeniye Inlet	1988	2 (No. 538)	1.0	1.0

Table 9. Estimated radioactivity in the SNF at the time of disposal for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Actinides												
$^{239+240}Pu$	94	474	1,080	1,080	33	167	55	280	--	--	1,263	2,001
^{241}Am	1	149	146	254	1	58	4	190	--	--	152	651
^{238}Pu	23	320	478	479	9	123	10	135	--	--	519	1,057
^{241}Pu	449	22,000	66,300	69,600	168	8,210	140	6,250	--	--	67,057	106,060
Subtotal	567	22,943	68,004	71,413	210	8,558	209	6,855	--	--	68,991	109,769
All	573	23,100	68,300	72,000	212	8,640	212	6,860	--	--	69,297	110,600
Fission Products												
^{129}I	0.02	0.03	0.04	0.04	0.009	0.009	0.01	0.02	--	--	0.08	0.09
^{90}Sr	89,900	100,000	112,000	115,000	31,400	35,200	42,800	44,500	--	--	276,100	294,700
^{134}Cs	3,930	36,000	37,200	52,100	1,320	13,400	90	328	--	--	42,540	101,828
^{137}Cs	97,900	104,000	128,000	131,000	34,300	36,700	46,700	46,700	--	--	306,900	318,400
^{154}Eu	1,450	1,810	2,430	2,630	532	678	347	347	--	--	4,759	5,465
^{125}Sb	2,500	6,620	9,540	12,300	813	2,340	142	192	--	--	12,995	21,452
^{147}Pm	125,000	253,000	157,000	297,000	40,100	88,700	5,350	6,320	--	--	327,450	645,020
^{155}Eu	1,570	2,430	3,150	3,620	527	850	253	275	--	--	5,500	7,175
^{99}Tc	15	15	18	18	5	5	9	9	--	--	47	48
^{151}Sm	852	1,690	1,140	1,140	287	584	513	950	--	--	2,792	4,364
Subtotal	323,117	505,565	450,478	614,808	109,284	178,457	96,203	99,621	--	--	979,083	1,398,452
All	663,000	2,300,000	1,990,000	4,170,000	213,000	811,000	187,000	191,000	--	--	3,053,000	7,472,000

Table 10. Estimated radioactivity of selected activation products in the reactor components and primary system corrosion products at the time of disposal for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Reactor Components												
^{60}Co	87,700	102,000	33,500	38,200	8,580	12,700	5,250	5,250	25,500	25,500	160,530	183,650
^{14}C	92	92	34	34	11	11	23	23	23	23	183	183
^{63}Ni	41,300	41,600	15,500	15,600	5,110	5,220	9,600	9,600	10,400	10,400	81,910	82,420
^{55}Fe	374,500	488,000	142,000	183,000	28,500	61,100	5,810	5,810	122,000	122,000	672,810	859,910
^{59}Ni	374	374	140	140	47	47	94	94	94	94	749	749
All	503,966	632,066	191,174	236,974	42,248	79,078	20,777	20,777	158,017	158,017	916,182	1,126,912
Primary System Corrosion Products												
^{60}Co	748	868	286	326	73	109	45	45	217	217	1,369	1,565
^{14}C	0.0001	0.0001	0.00005	0.00005	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.0003	0.0003
^{63}Ni	2	2	1	1	0.3	0.3	0.5	0.5	1	1	4	4
^{55}Fe	12	15	5	6	1	2	0	0	4	4	21	27
^{59}Ni	0.01	0.01	0.004	0.004	0.001	0.001	0.003	0.003	0.003	0.003	0.02	0.02
All	762	886	291	333	74	111	45	45	221	221	1,394	1,596

Table 11. Estimated radioactivity in the SNF at the present time (1993) for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Actinides												
$^{239+240}Pu$	94	474	1,080	1,080	33	167	55	280	--	--	1,263	2,001
^{241}Am	14	605	1,750	1,780	5	204	6	277	--	--	1,774	2,866
^{238}Pu	18	258	390	393	7	105	9	123	--	--	424	879
^{241}Pu	117	5,710	19,000	19,900	61	2,990	79	3,510	--	--	19,257	32,110
Subtotal	243	7,047	22,220	23,153	106	3,466	149	4,190	--	--	22,718	37,856
All	247	7,050	22,250	23,200	108	3,450	152	4,190	--	--	22,757	37,890
Fission Products												
^{129}I	0.02	0.03	0.04	0.04	0.009	0.009	0.01	0.02	--	--	0.08	0.09
^{90}Sr	46,200	51,400	60,500	62,000	19,000	21,400	32,100	33,400	--	--	157,800	168,200
^{134}Cs	0.3	3	6	8	1	12	2	6	--	--	9	29
^{137}Cs	51,300	54,600	70,500	72,100	21,100	22,600	35,400	35,400	--	--	178,300	184,700
^{154}Eu	152	190	299	324	98	125	132	132	--	--	681	771
^{125}Sb	2	6	14	18	4	12	7	9	--	--	27	45
^{147}Pm	63	155	237	309	128	345	225	365	--	--	653	1,174
^{155}Eu	31	49	54	62	28	45	47	51	--	--	161	207
^{99}Tc	15	15	18	18	5	5	9	9	--	--	47	48
^{151}Sm	686	1,360	930	937	244	496	468	866	--	--	2,328	3,659
Subtotal	98,449	107,777	132,559	135,777	40,608	45,040	68,389	70,238	--	--	340,006	358,833
All	195.000	213,000	262,000	269,000	80,500	86,700	136,000	139,000	--	--	673,500	707,700

Table 12. Estimated radioactivity of selected activation products in the reactor components and primary system corrosion products at the present time (1993) for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Reactor Components												
^{60}Co	2,297	2,654	1,100	1,250	542	804	1,080	1,080	13,200	13,200	18,219	18,988
^{14}C	91	91	34	34	11	11	23	23	23	23	182	182
^{63}Ni	34,140	34,420	13,000	13,100	4,420	4,510	8,480	8,480	10,100	10,100	70,140	70,610
^{55}Fe	336	429	193	249	138	296	276	276	34,300	34,300	35,243	35,550
^{59}Ni	374	374	140	140	47	47	94	94	94	94	749	749
All	37,238	37,968	14,467	14,773	5,158	5,668	9,953	9,953	57,717	57,717	124,533	126,079
Primary System Corrosion Products												
^{60}Co	20	23	9	11	5	7	9	9	113	113	156	162
^{14}C	0.0001	0.0001	0.00005	0.00005	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.0002	0.0002
^{63}Ni	1.7	1.7	0.6	0.7	0.2	0.2	0.4	0.4	0.5	0.5	3.5	3.5
^{55}Fe	0.01	0.01	0.006	0.008	0.004	0.009	0.009	0.009	1.1	1.1	1.1	1.1
^{59}Ni	0.01	0.01	0.004	0.004	0.001	0.001	0.003	0.003	0.003	0.003	0.02	0.02
All	21	24	10	11	5	7	10	10	115	115	161	167

Table 13. Estimated radioactivity in the SNF at twenty years hence (2013) for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Actinides												
$^{239+240}Pu$	94	474	1,079	1,079	33	167	55	280	--	--	1,262	2,000
^{241}Am	16	701	2,078	2,126	6	258	8	339	--	--	2,107	3,424
^{238}Pu	15	220	333	336	6	90	8	105	--	--	362	751
^{241}Pu	45	2,181	7,257	7,601	23	1,142	30	1,341	--	--	7,355	12,264
Subtotal	170	3,576	10,748	11,141	68	1,656	101	2,065	--	--	11,086	18,438
All	170	3,576	10,748	11,141	68	1,656	101	2,065	--	--	11,086	18,438
Fission Products												
^{129}I	0.02	0.03	0.04	0.04	0.009	0.009	0.01	0.02	--	--	0.08	0.09
^{90}Sr	28,408	31,605	37,201	38,123	11,683	13,159	19,738	20,537	--	--	97,029	103,424
^{134}Cs	0.0004	0.004	0.007	0.01	0.001	0.01	0.002	0.007	--	--	0.01	0.03
^{137}Cs	32,320	34,399	44,417	45,425	13,293	14,239	22,303	22,303	--	--	112,333	116,365
^{154}Eu	31	39	62	67	20	26	27	27	--	--	141	160
^{125}Sb	0.01	0.04	0.09	0.1	0.03	0.08	0.04	0.06	--	--	0.2	0.3
^{147}Pm	0.3	0.8	1.2	1.6	0.6	1.7	1.1	1.8	--	--	3.3	5.9
^{155}Eu	2	3	3	4	2	3	3	3	--	--	10	13
^{99}Tc	15	15	18	18	5	5	9	9	--	--	47	48
^{151}Sm	588	1,166	797	803	209	425	401	742	--	--	1,996	3,137
Subtotal	61,364	67,229	82,499	84,442	25,213	27,858	42,482	43,624	--	--	211,559	223,152
All	120,344	131,372	161,714	165,532	49,471	54,485	83,316	85,257	--	--	414,844	436,646

Table 14. Estimated radioactivity of selected activation products in the reactor components and primary system corrosion products at twenty years hence (2013) for the former Soviet Union naval reactors dumped in the Kara Sea.

	Disposal site activity range (Ci)											
Nuclide	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Reactor Components												
^{60}Co	166	191	79	90	39	58	78	78	951	951	1,313	1,369
^{14}C	91	91	34	34	11	11	23	23	23	23	182	182
^{63}Ni	29,726	29,969	11,319	11,406	3,848	3,927	7,384	7,384	8,794	8,794	61,071	61,480
^{55}Fe	2	3	1	2	1	2	2	2	214	214	220	222
^{59}Ni	374	374	140	140	47	47	94	94	94	94	749	749
All	30,358	30,628	11,573	11,672	3,946	4,045	7,580	7,580	10,076	10,076	63,534	64,001
Primary System Corrosion Products												
^{60}Co	1.4	1.6	0.7	0.8	0.3	0.5	0.7	0.7	8.1	8.1	11.2	11.7
^{14}C	0.0001	0.0001	0.00005	0.00005	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.0002	0.0002
^{63}Ni	1.5	1.5	0.6	0.6	0.2	0.2	0.4	0.4	0.4	0.4	3.1	3.1
^{55}Fe	0.00007	0.00008	0.00004	0.00005	0.00003	0.00006	0.00005	0.00005	0.007	0.007	0.007	0.007
^{59}Ni	0.01	0.01	0.004	0.004	0.001	0.001	0.003	0.003	0.003	0.003	0.02	0.02
All	2.9	3.1	1.2	1.3	0.5	0.7	1.1	1.1	8.6	8.6	14.3	14.8

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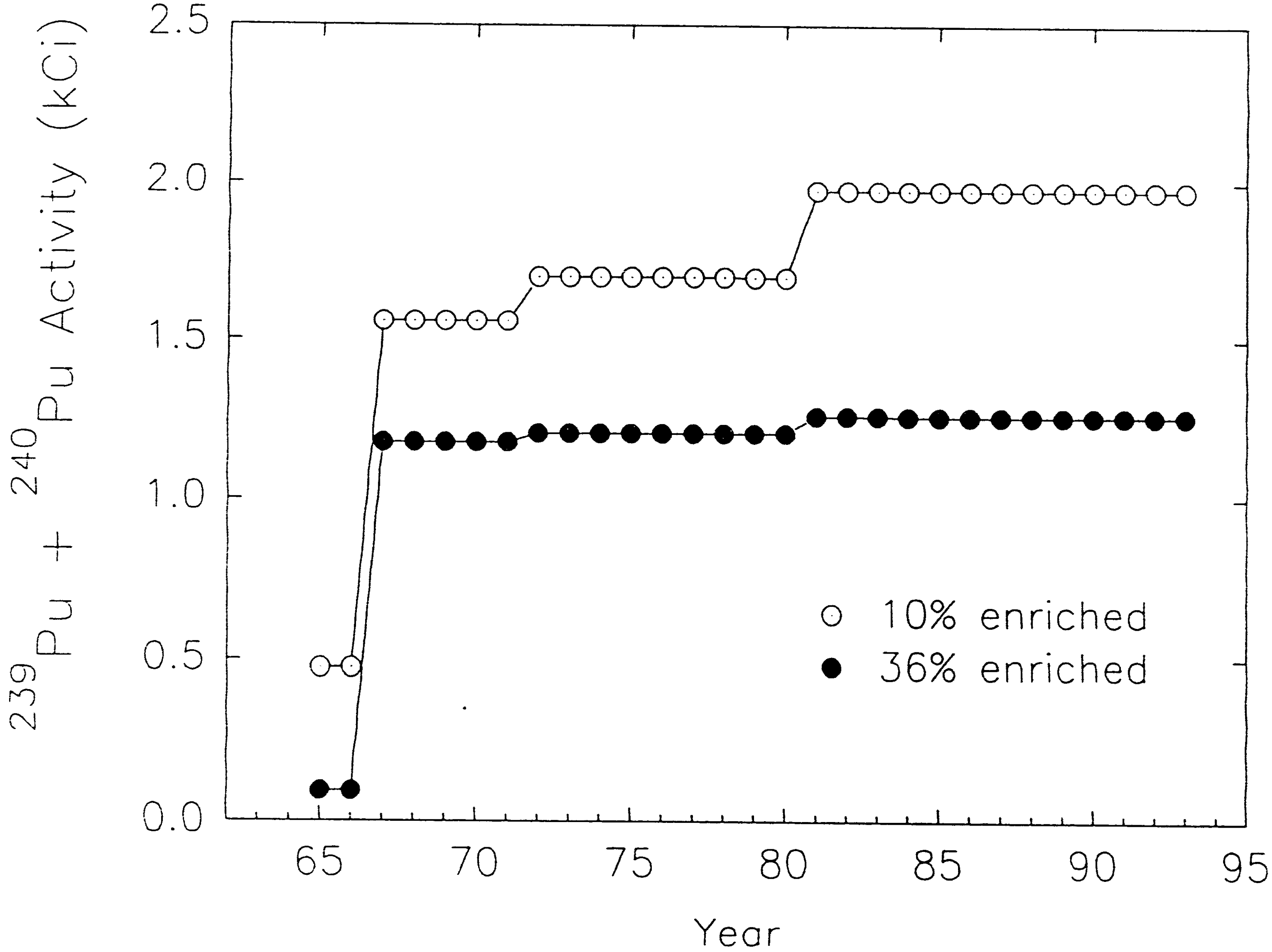
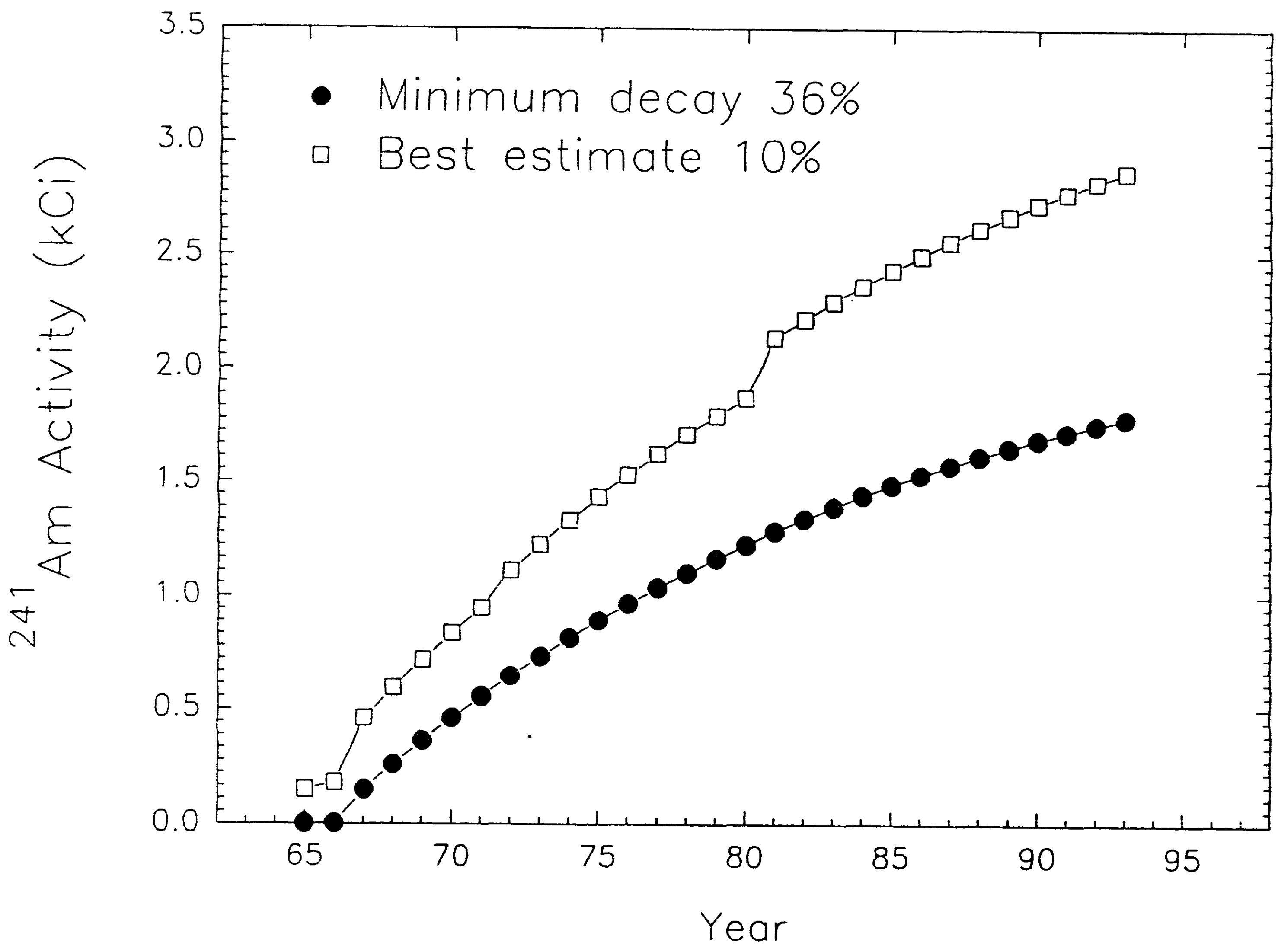
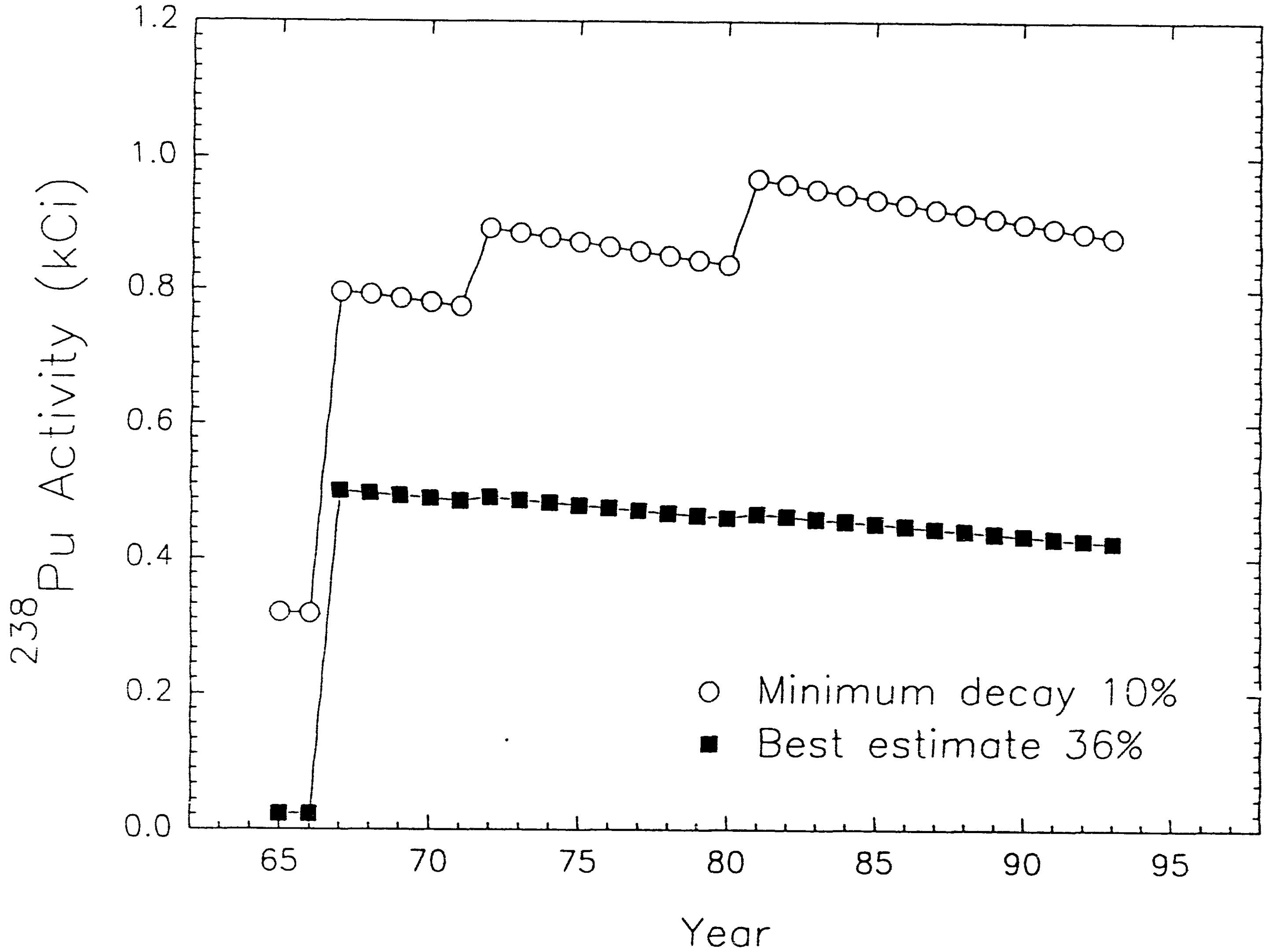


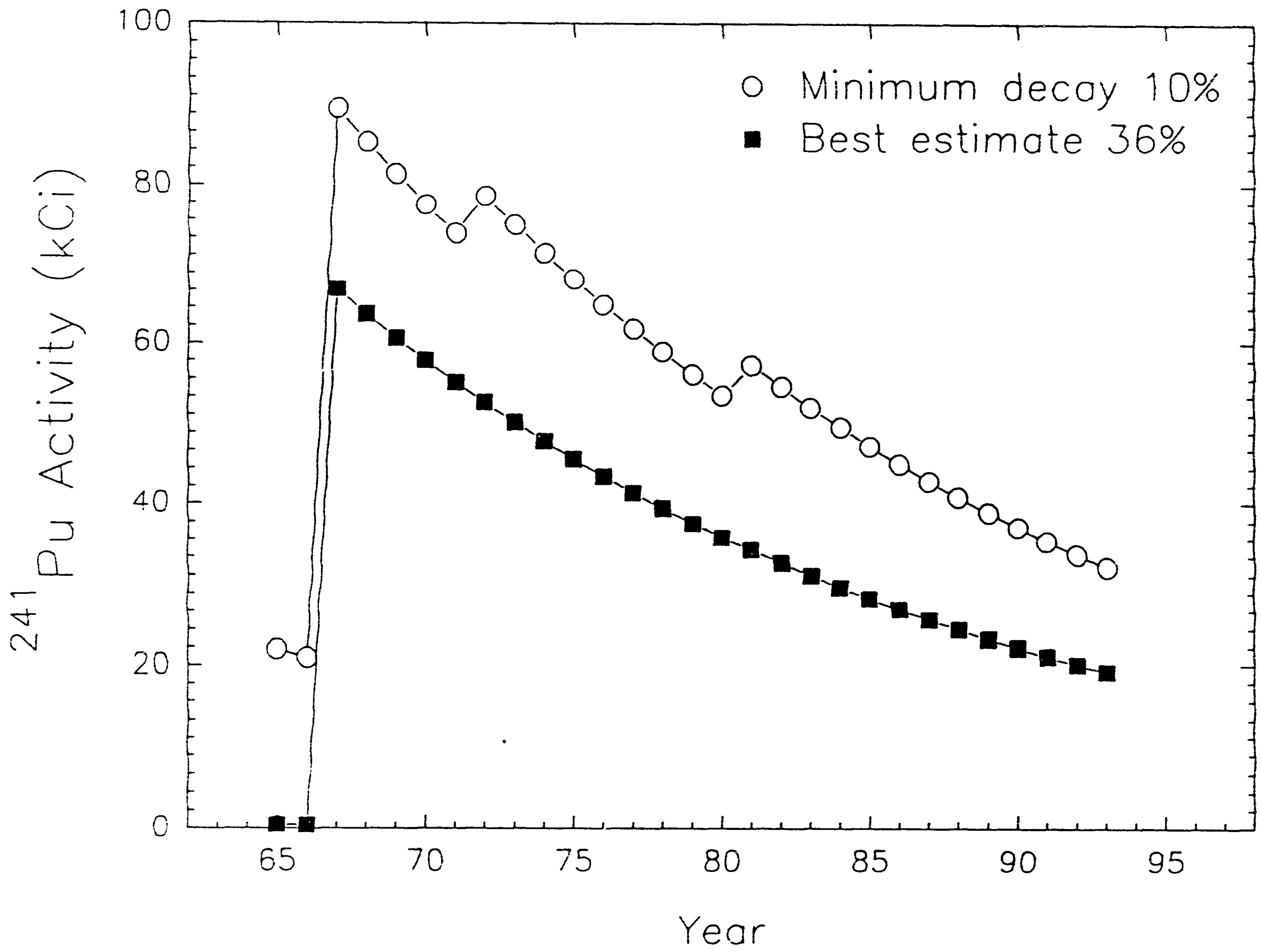
2.5
2.0
1.5
1.0
0.5
0.0
^{239}Pu + ^{240}Pu Activity (kCi)
65
70
75
80
85
90
95
Year
10% enriched
36% enriched



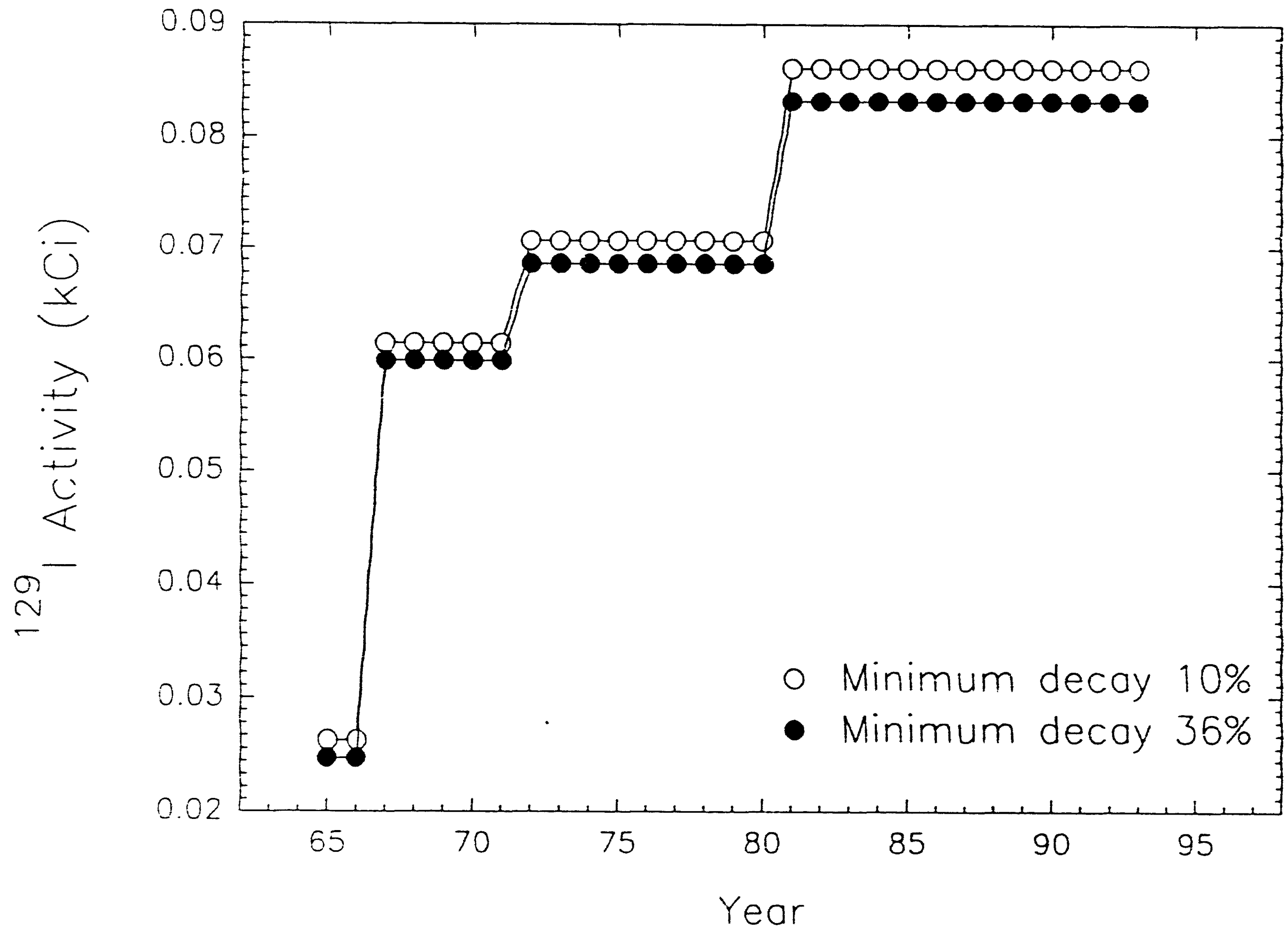
Minimum decay 36%
Best estimate 10%
241Am Activity (kCi)
Year
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
65
70
75
80
85
90
95



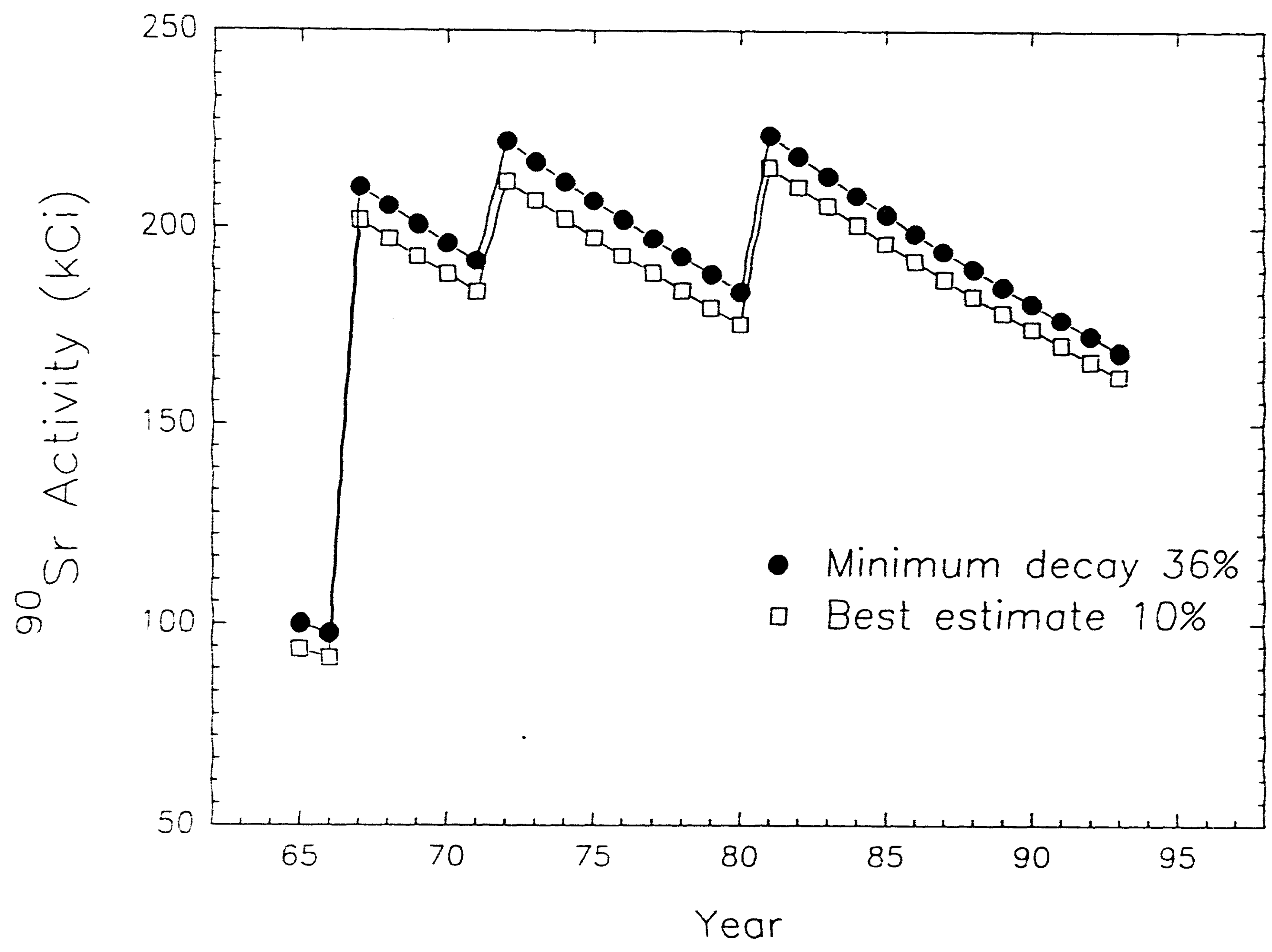
1.2
1.0
0.8
0.6
0.4
0.2
0.0
238Pu Activity (kCi)
65
70
75
80
85
90
95
Year
Minimum decay 10%
Best estimate 36%



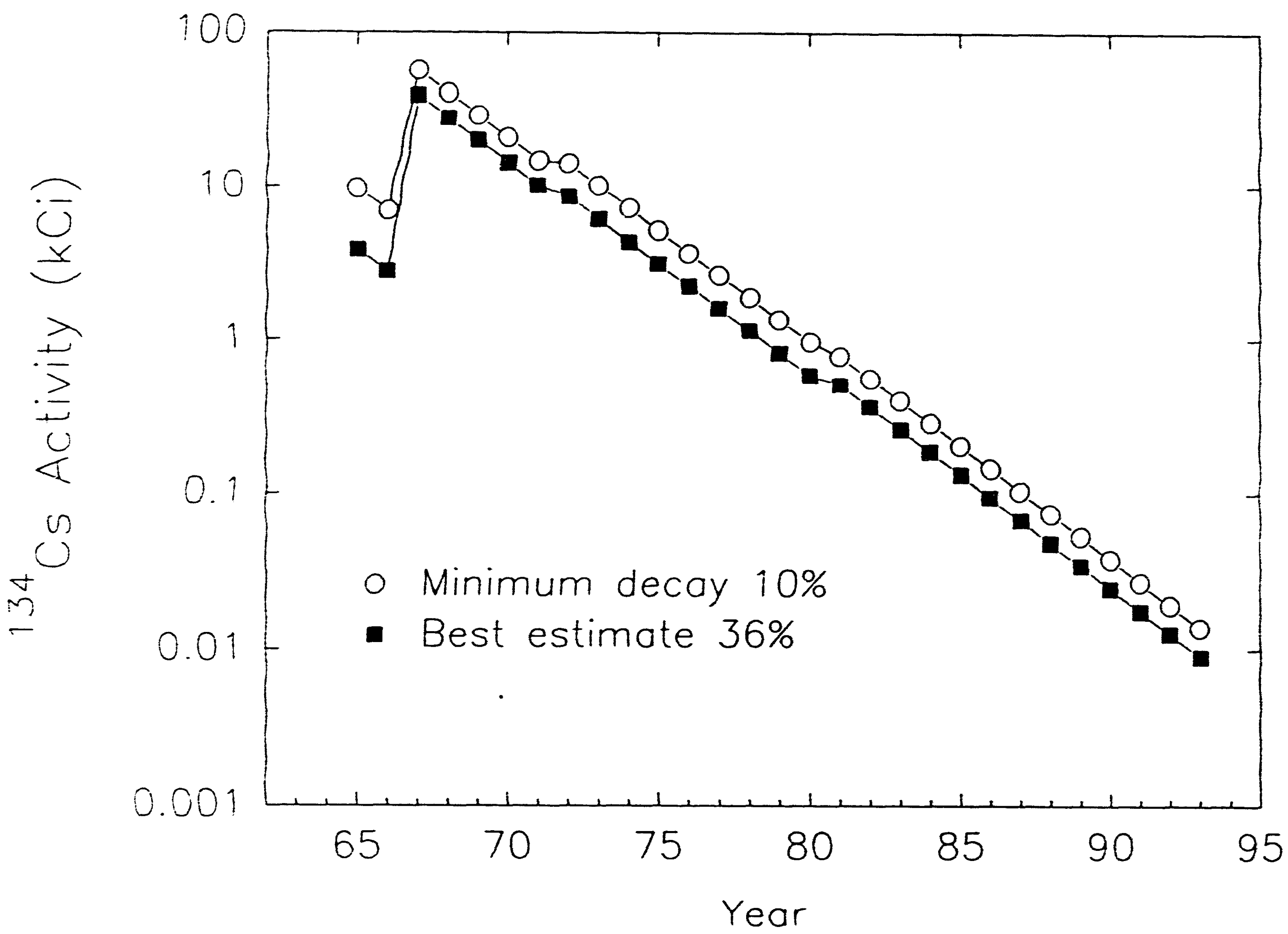
Minimum decay 10%
Best estimate 36%
241Pu Activity (kCi)
Year
0
20
40
60
80
100
65
70
75
80
85
90
95



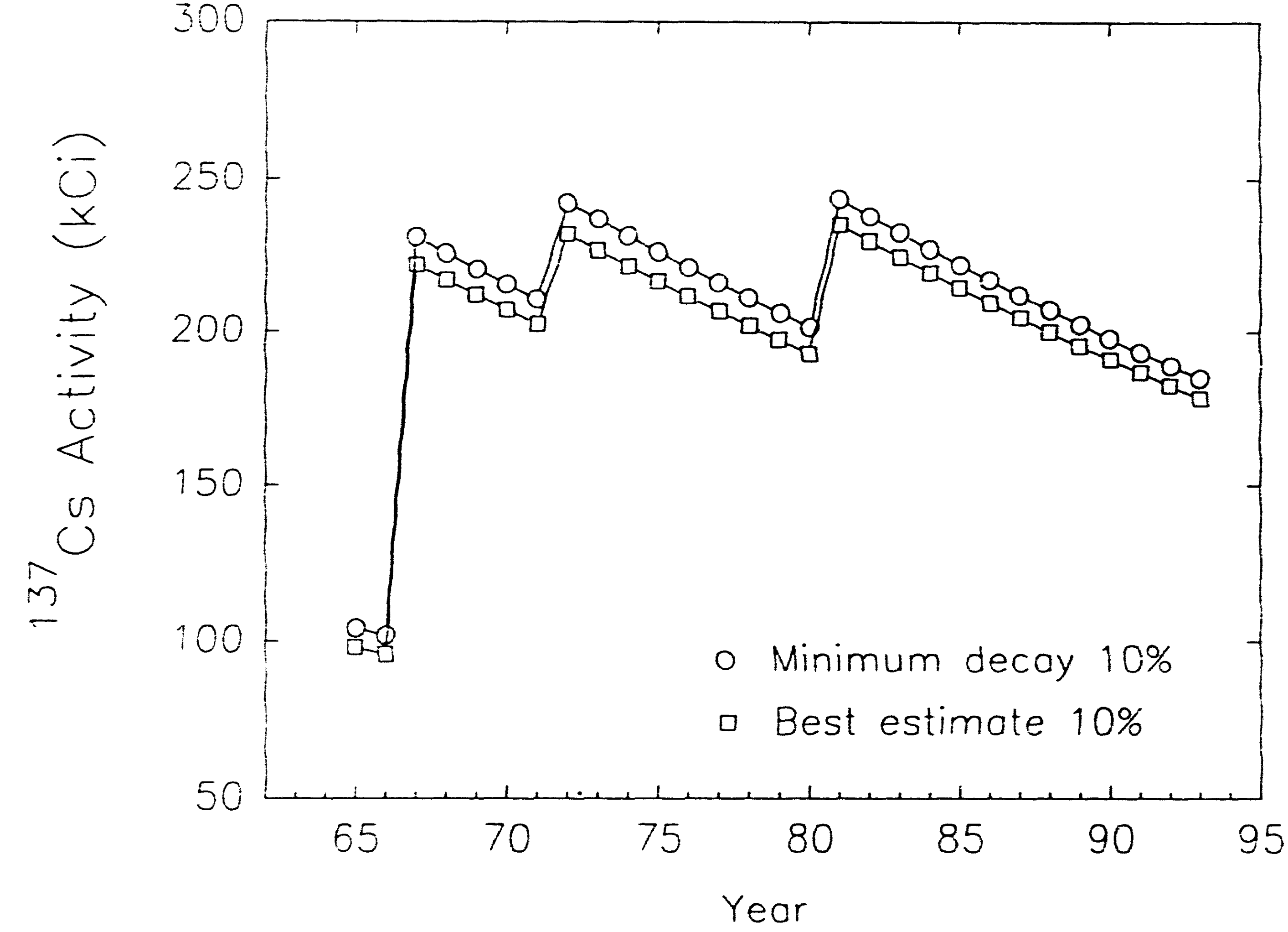
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
129 I Activity (kCi)
65
70
75
80
85
90
95
Year
Minimum decay 10%
Minimum decay 36%



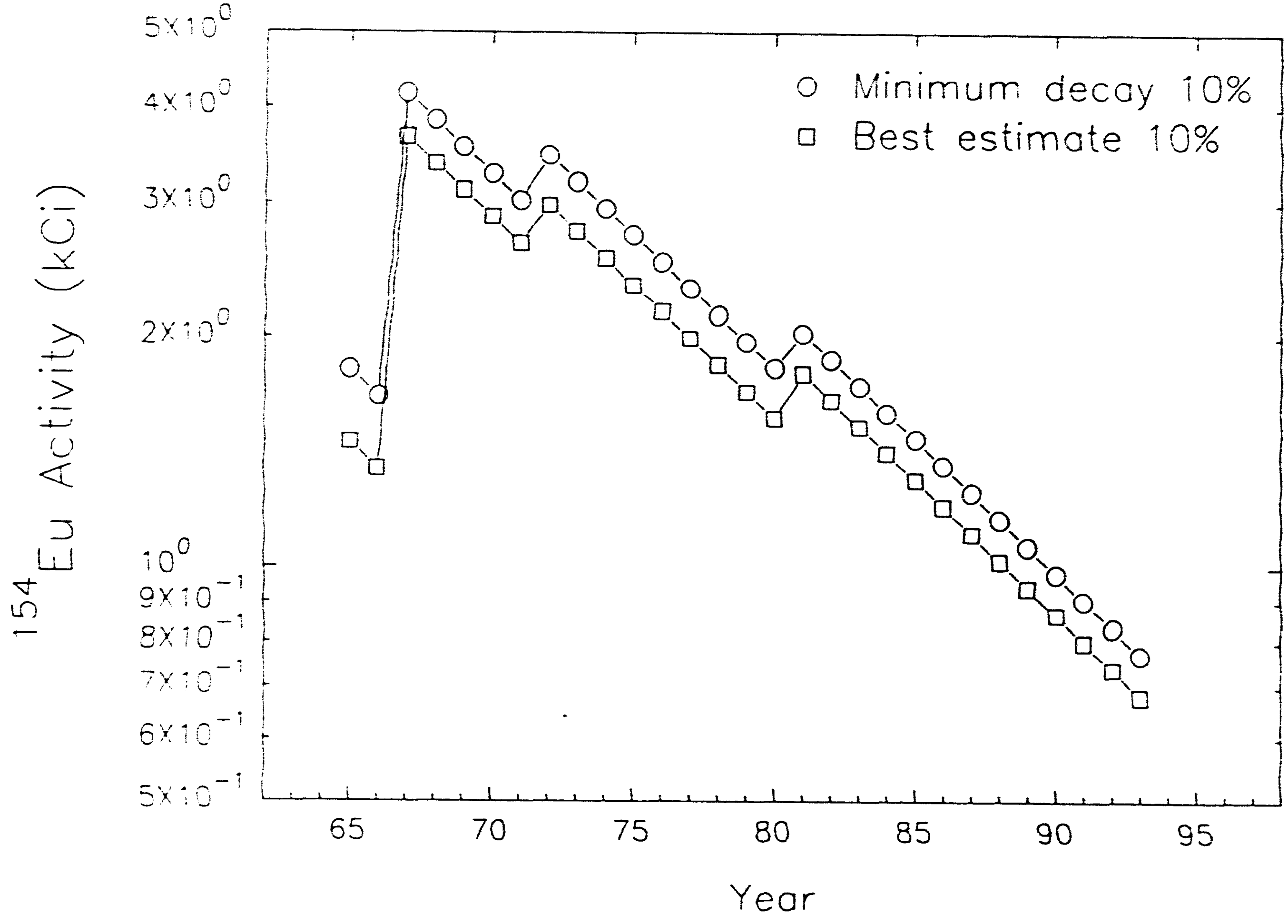
250
200
150
100
50
90Sr Activity (kCi)
65
70
75
80
85
90
95
Year
Minimum decay 36%
Best estimate 10%

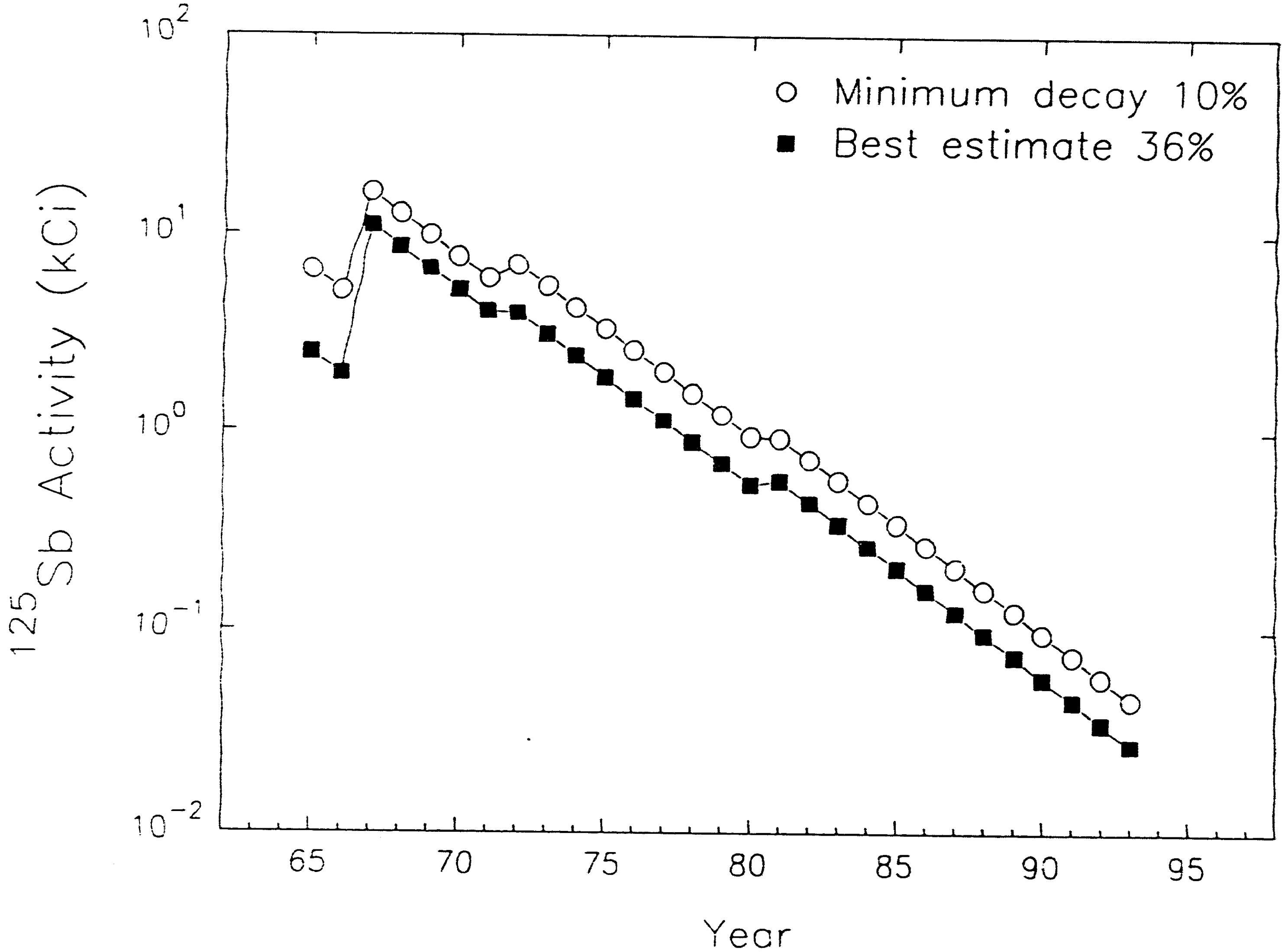


100
10
1
0.1
0.01
0.001
134Cs Activity (kCi)
65
70
75
80
85
90
95
Year
Minimum decay 10%
Best estimate 36%

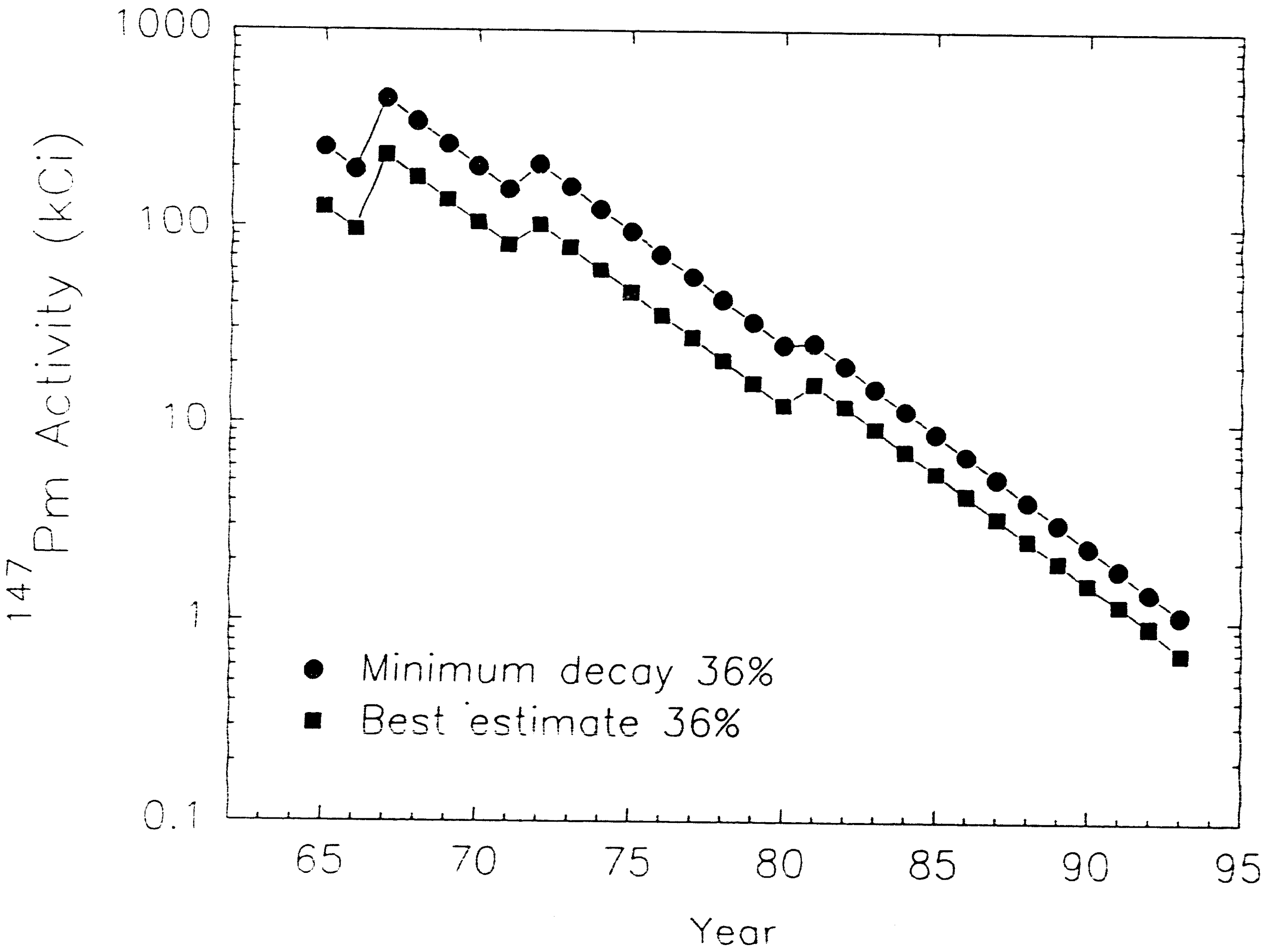


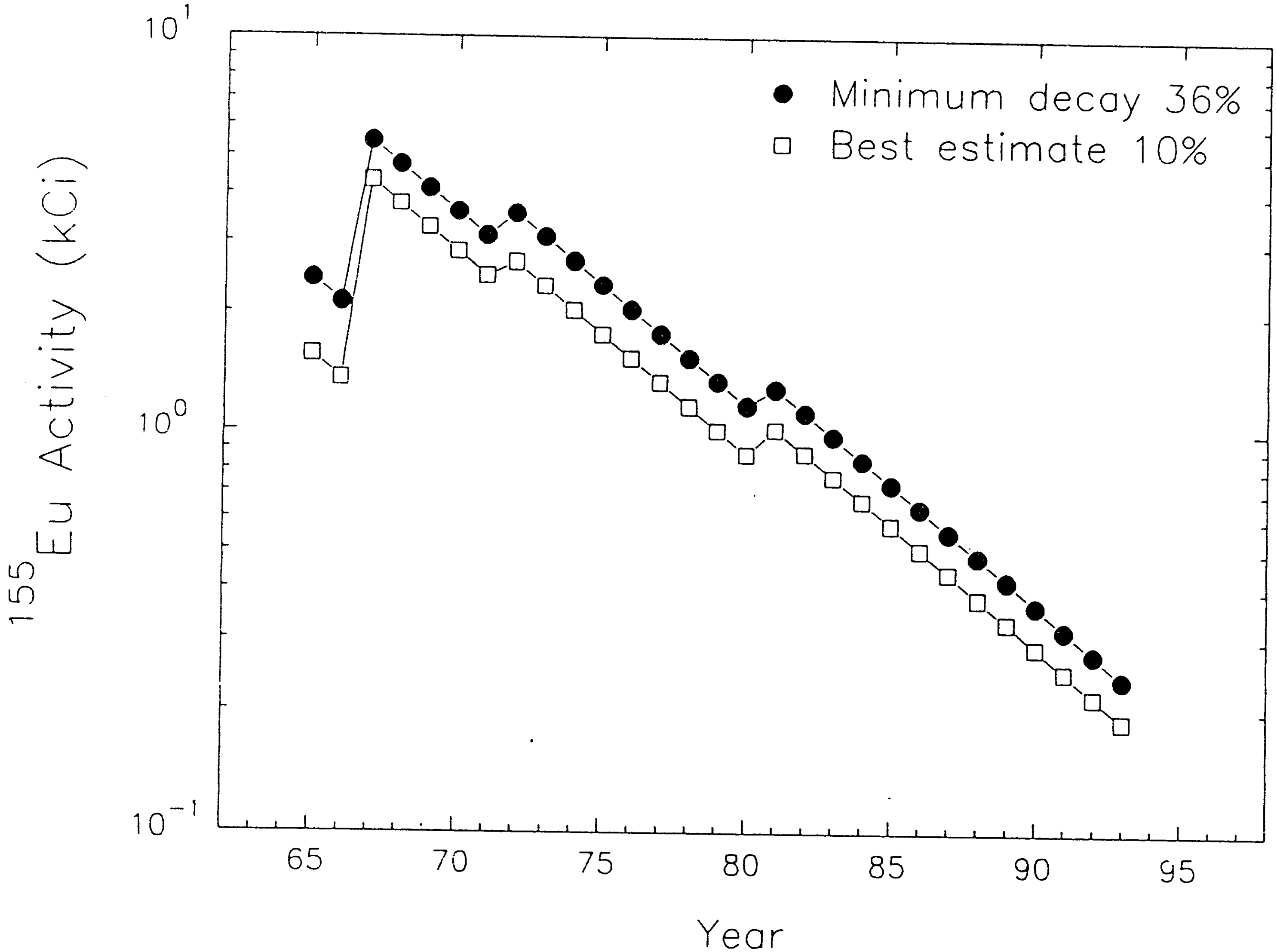
300
250
200
150
100
50
65
70
75
80
85
90
95
Year
137Cs Activity (kCi)
Minimum decay 10%
Best estimate 10%

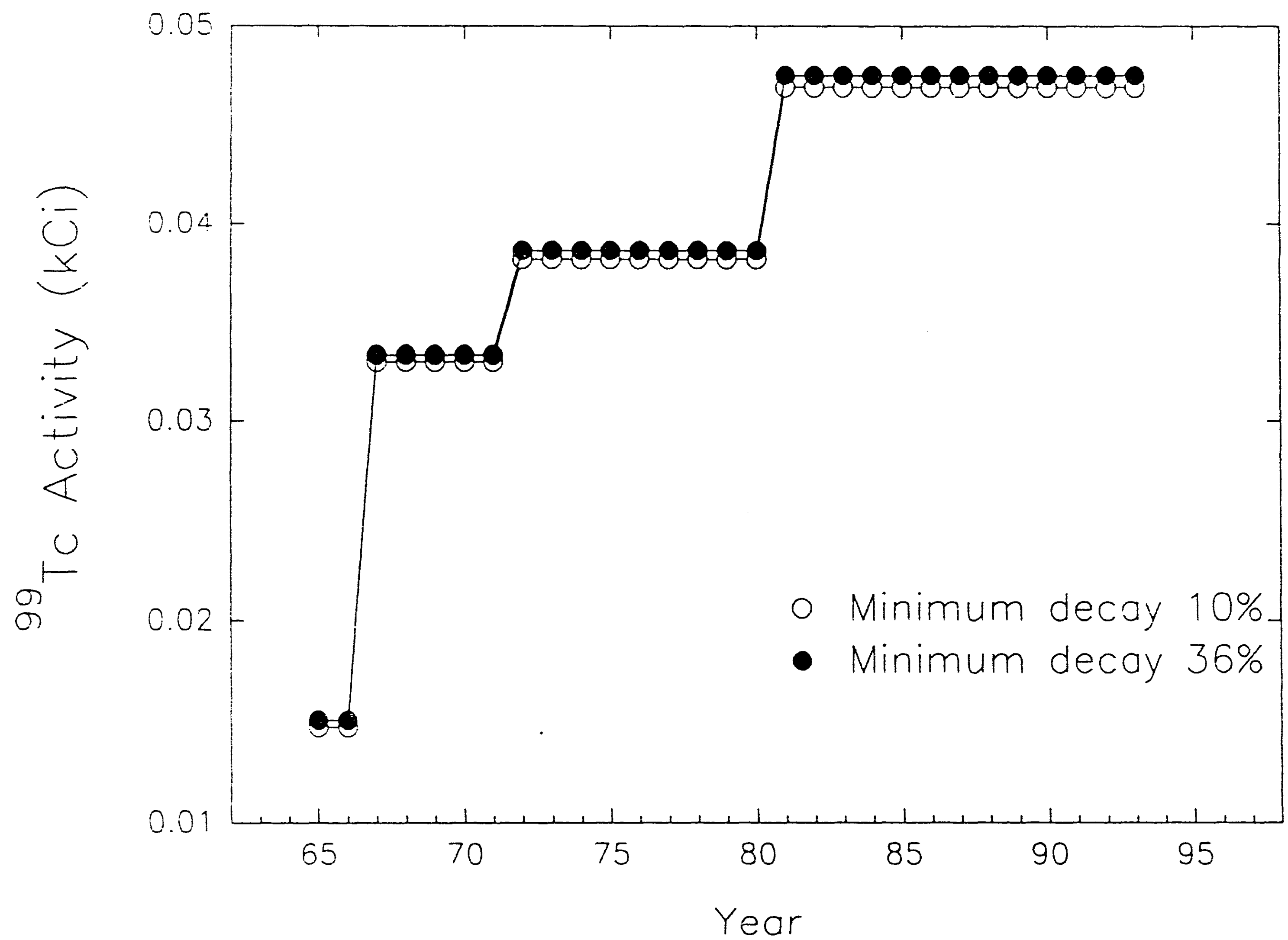

Minimum decay 10%
Best estimate 10%
154Eu Activity (kCi)
5X10^0
4X10^0
3X10^0
2X10^0
10^0
9X10^-1
8X10^-1
7X10^-1
6X10^-1
5X10^-1
65
70
75
80
85
90
95
Year

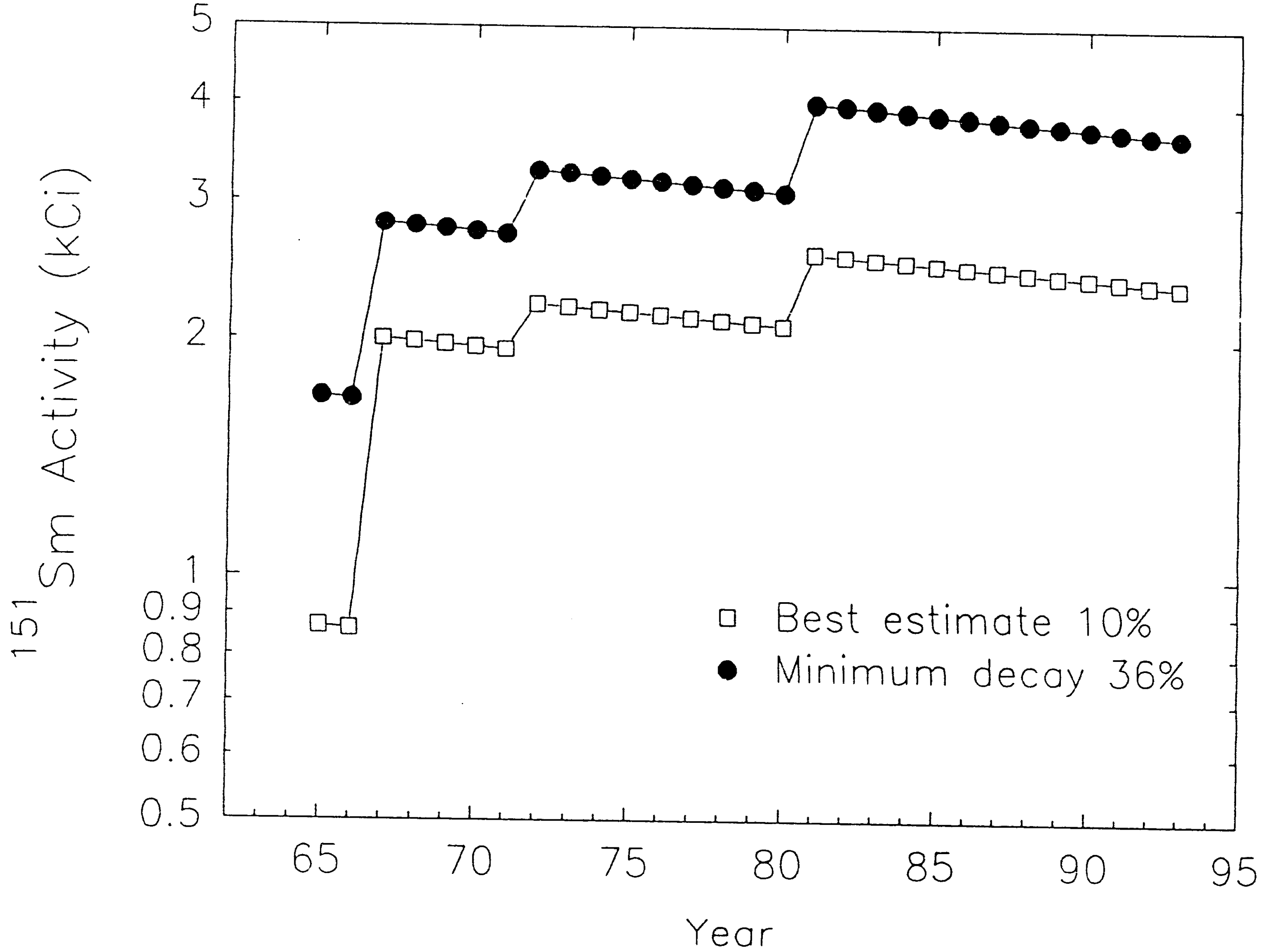


Minimum decay 10%
Best estimate 36%
^{125}Sb Activity (kCi)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
65
70
75
80
85
90
95
Year

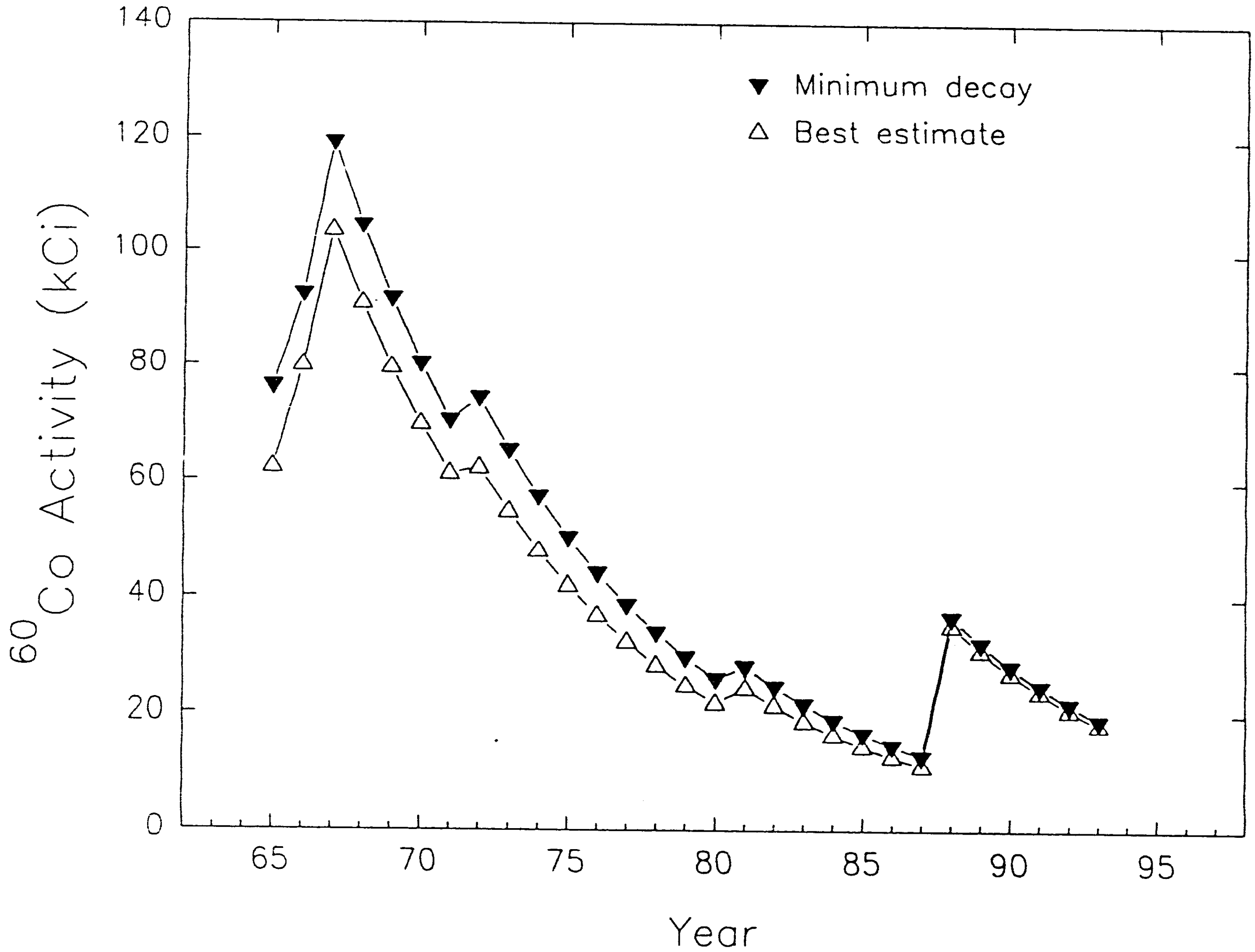

1000
100
10
1
0.1
147Pm Activity (kCi)
65
70
75
80
85
90
95
Year
Minimum decay 36%
Best estimate 36%


Minimum decay 36%
Best estimate 10%
^{155}Eu Activity (kCi)
10^{1}
10^{0}
10^{-1}
65
70
75
80
85
90
95
Year

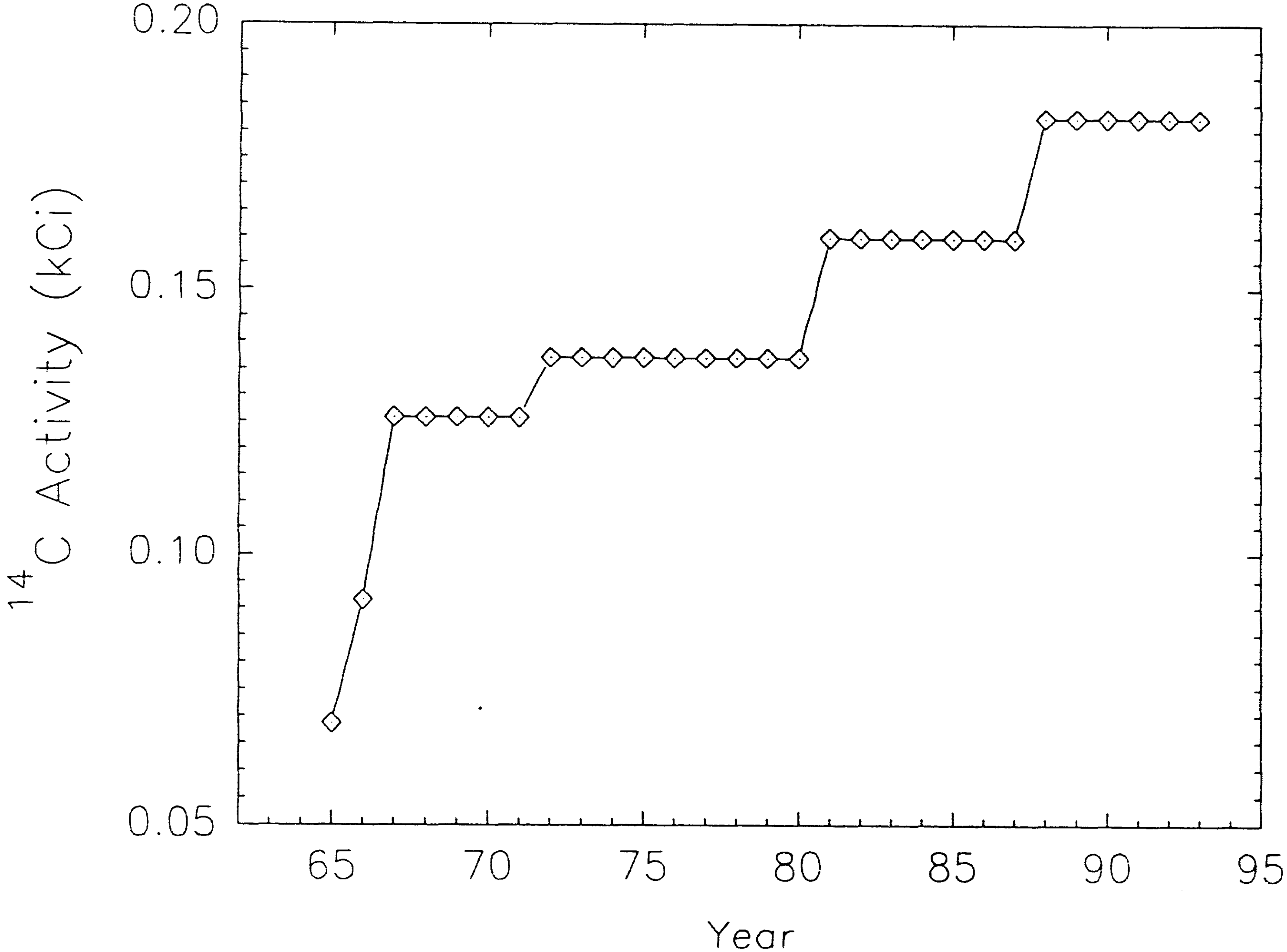

0.05
0.04
0.03
0.02
0.01
^{99}Tc Activity (kCi)
65
70
75
80
85
90
95
Year
Minimum decay 10%
Minimum decay 36%



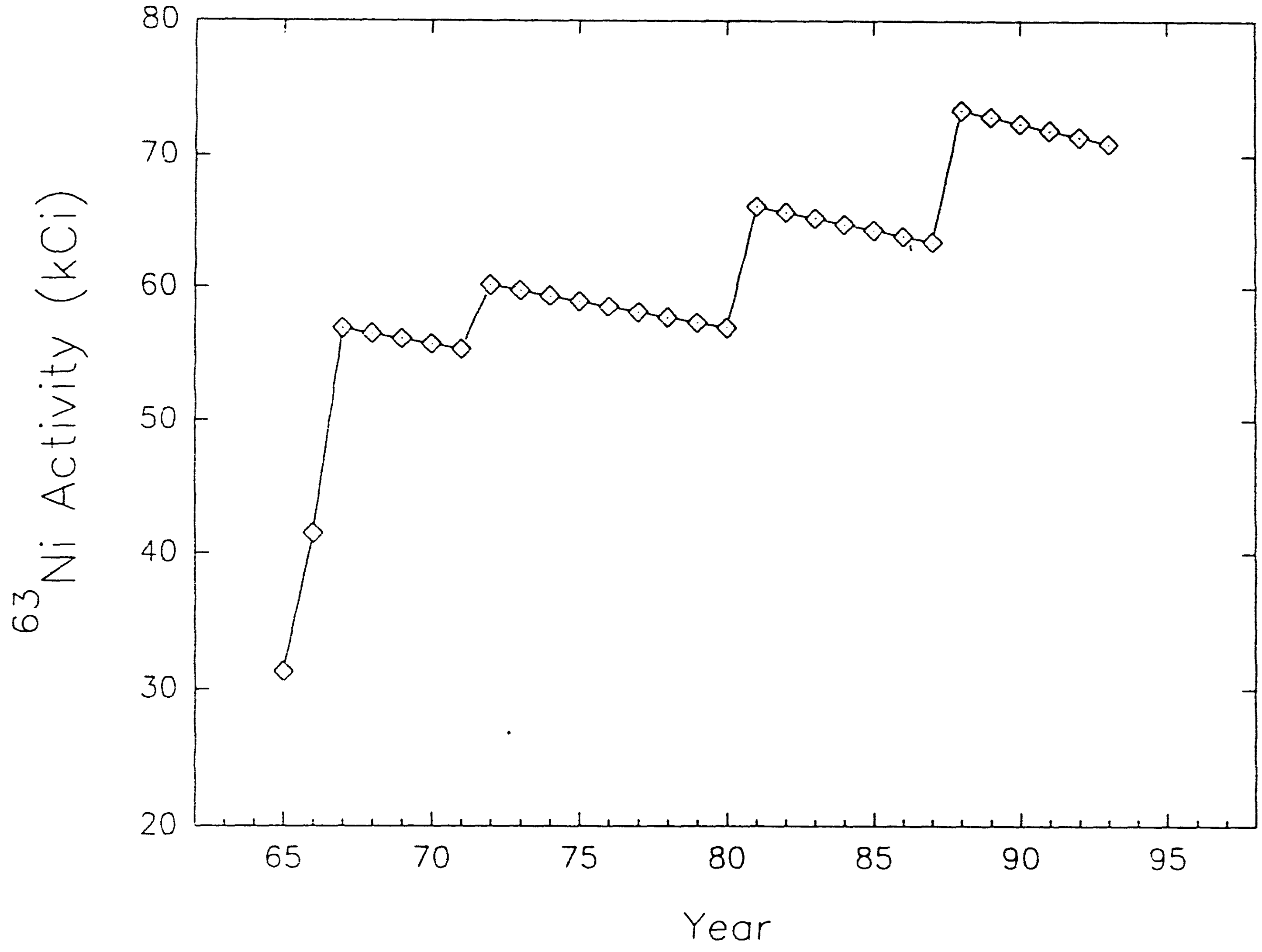
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
151Sm Activity (kCi)
65
70
75
80
85
90
95
Year
Best estimate 10%
Minimum decay 36%



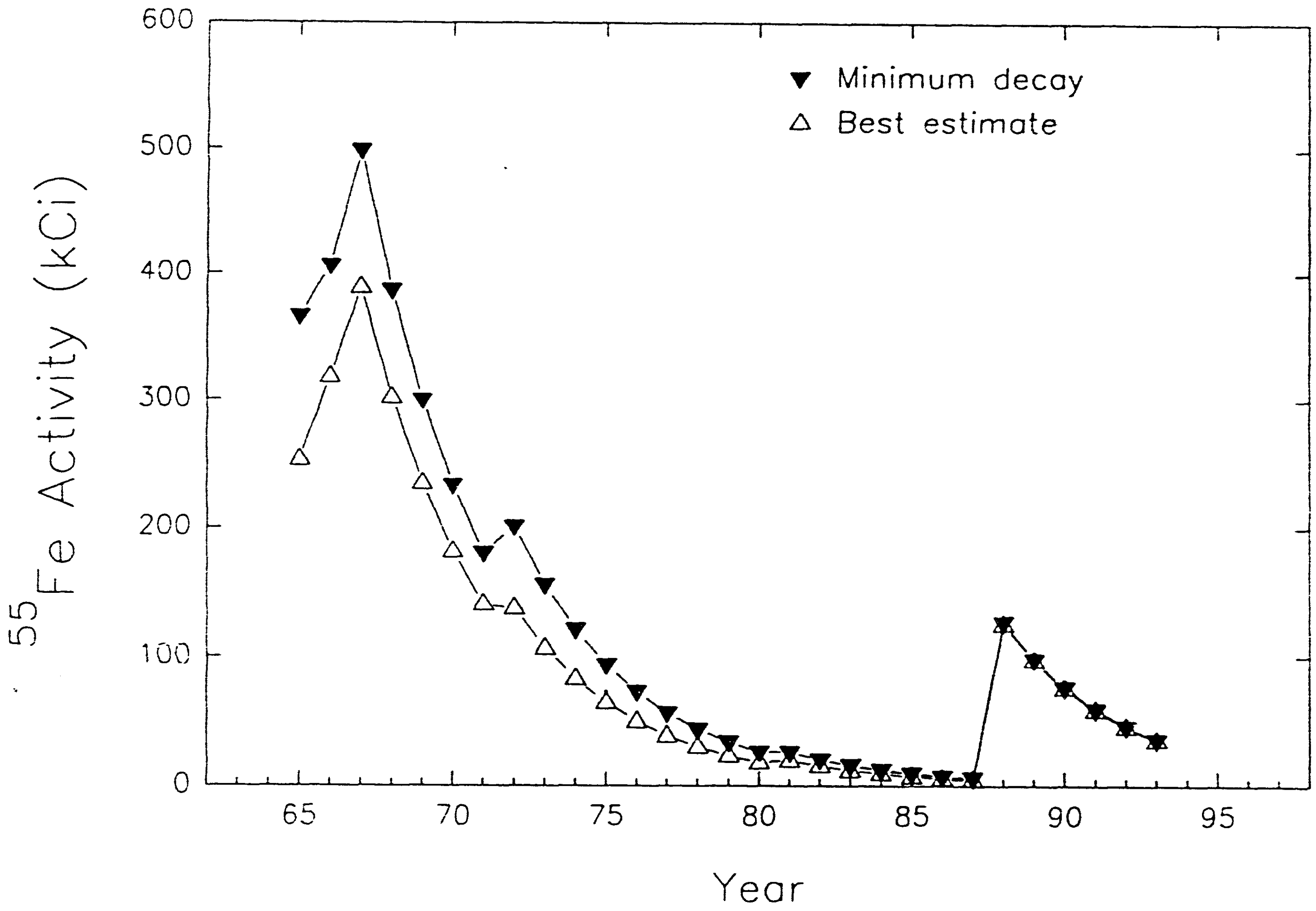
Minimum decay
Best estimate
140
120
100
80
60
40
20
0
65
70
75
80
85
90
95
60Co Activity (kCi)
Year



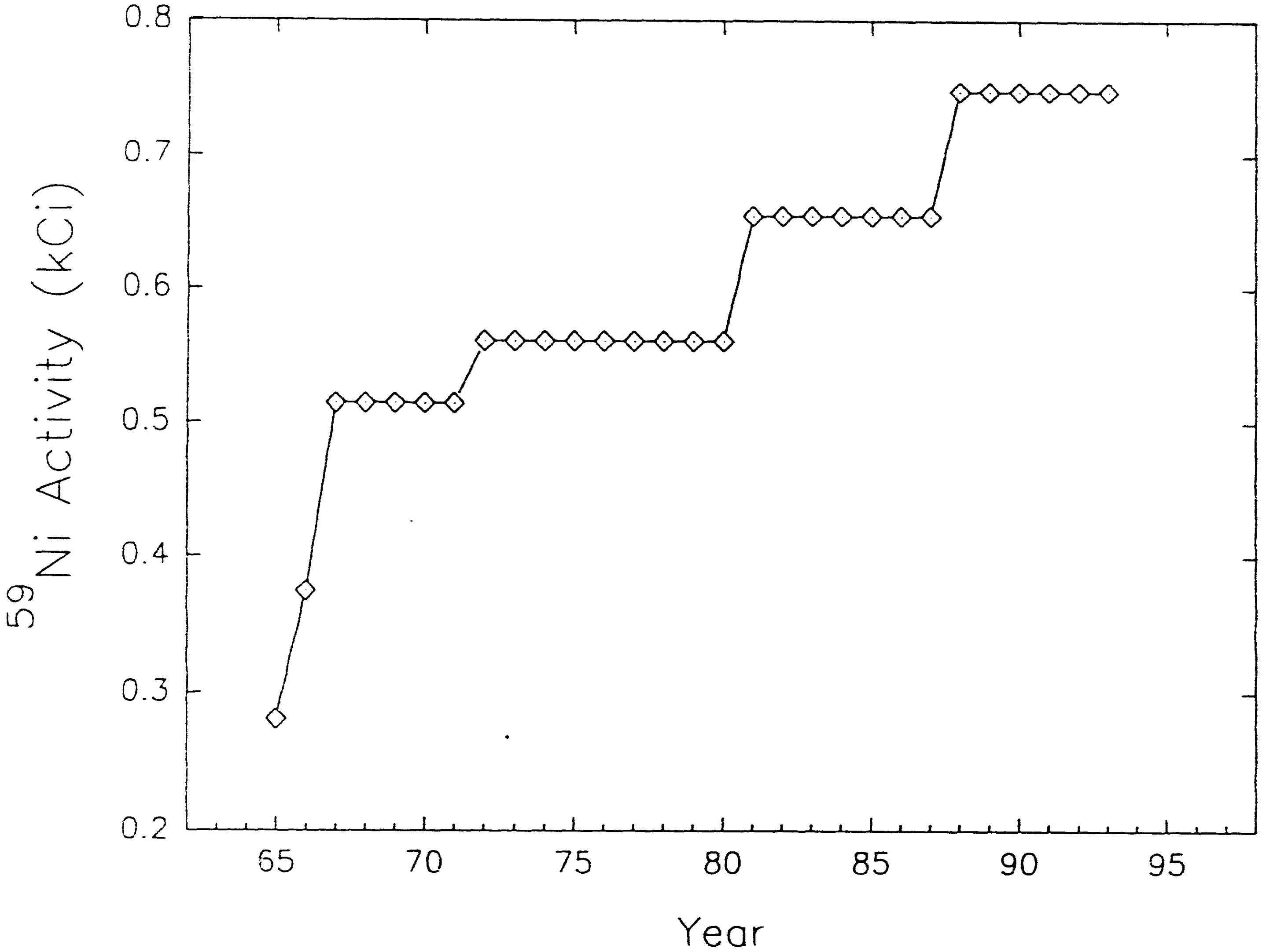
0.20
0.15
0.10
0.05
14C Activity (kCi)
65
70
75
80
85
90
95
Year



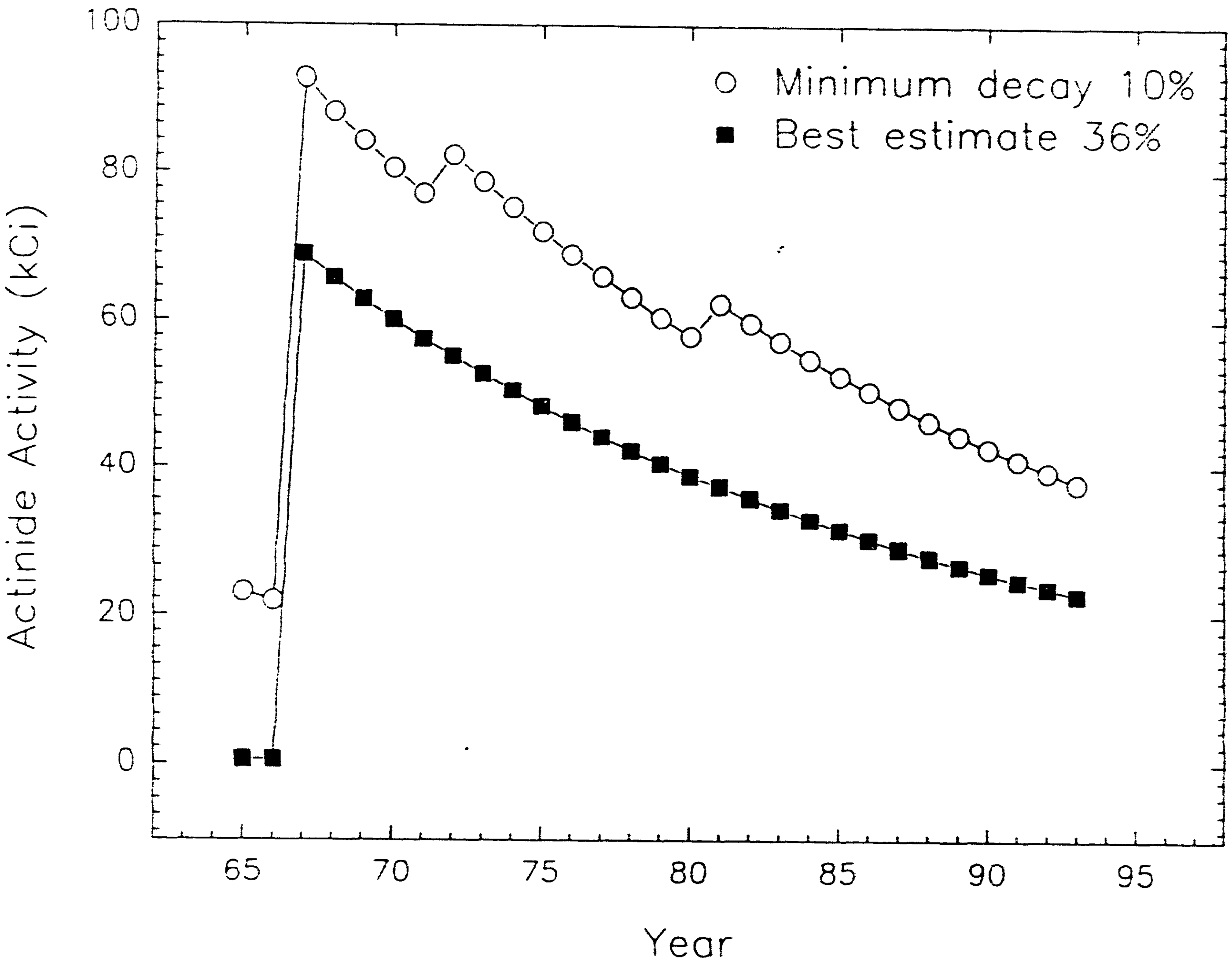
80
70
60
50
40
30
20
^{63}Ni Activity (kCi)
65
70
75
80
85
90
95
Year



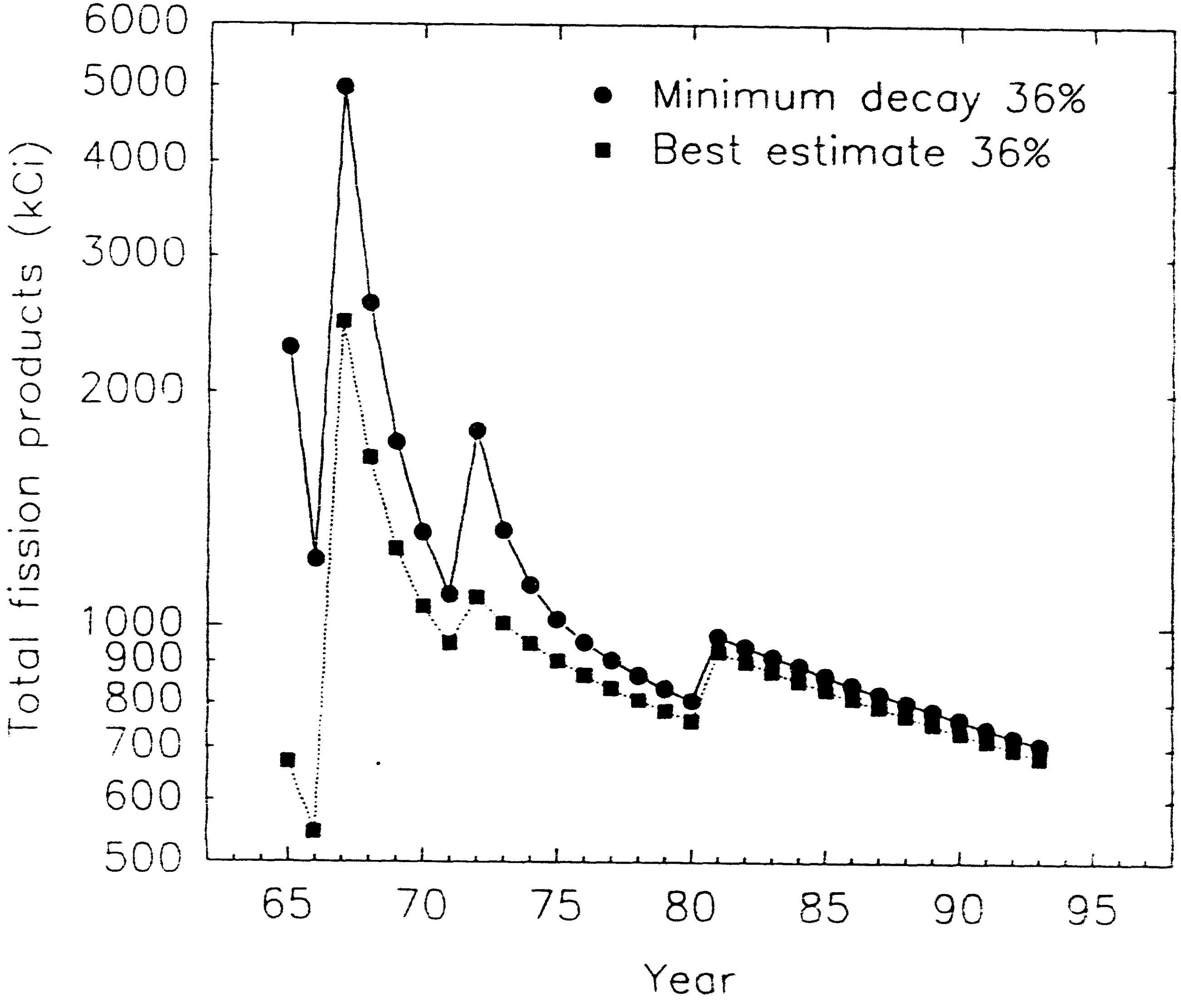
Minimum decay
Best estimate
600
500
400
300
200
100
0
65
70
75
80
85
90
95
^{55}Fe Activity (kCi)
Year



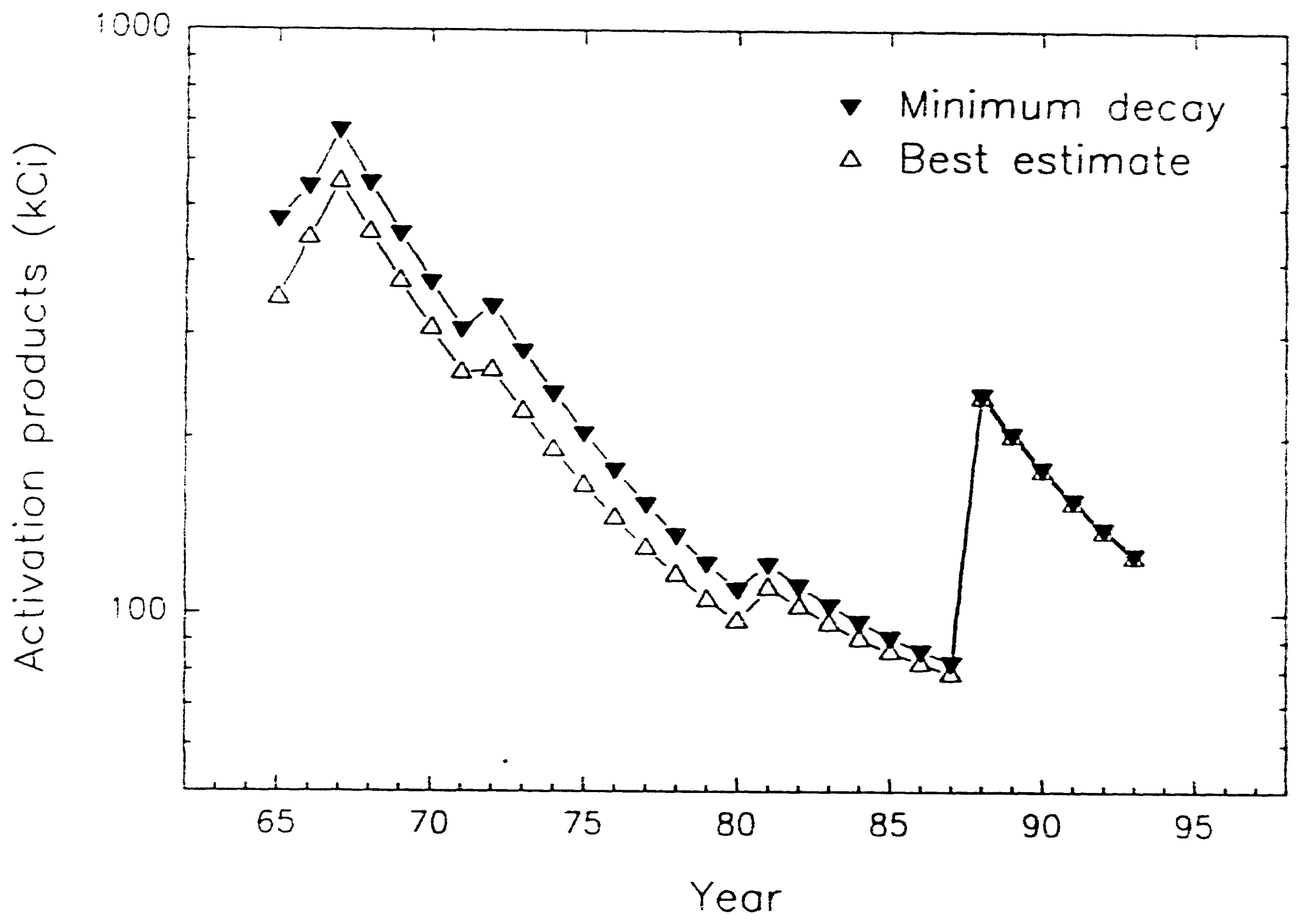
0.8
0.7
0.6
0.5
0.4
0.3
0.2
65
70
75
80
85
90
95
Year
^{59}Ni Activity (kCi)



Minimum decay 10%
Best estimate 36%
Actinide Activity (kCi)
Year
100
80
60
40
20
0
65
70
75
80
85
90
95



Minimum decay 36%
Best estimate 36%
Total fission products (kCi)
6000
5000
4000
3000
2000
1000
900
800
700
600
500
65
70
75
80
85
90
95
Year



Minimum decay
Best estimate
1000
100
Activation products (kCi)
65
70
75
80
85
90
95
Year

END

DATE FILMED

12/27/93