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HISTORICAL SURVEY OF NUCLEAR FUEL UTILIZATION IN U.S. LWR POWER PLANTS

FINAL REPORT

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August, 1979

Prepared Under Contract

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SOUTHERN SCIENCE APPLICATIONS, INC.

DIVISION OF BLACK & VEATCH

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U.S. Department of Energy
Division of Energy Technology

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FOREWORD

The Nonproliferation System Assessment Program (NASAP) and the International Fuel Cycle Evaluation (INFCE) have renewed interest, both domestically and internationally, in reassessing alternative strategies for the future development of nuclear energy. For the U.S. and much of the rest of the world, the baseline source of nuclear energy is the light water reactor (LWR). Furthermore, INFCE forecasts that by the end of the century well over 80% of nuclear energy will still be supplied by LWRs. For the U.S., an even higher percentage of nuclear energy is likely to be derived from LWRs.

One of the central issues of the NASAP and INFCE programs is the uranium resource utilization of the various alternative reactor systems. The projected consumption of uranium resources, relative to the projected reserves, is a critical determinant of the need for, and timing of, the introduction of advanced nuclear technologies to alleviate future pressures on uranium prices. Uncertainties in both future nuclear energy development and uranium availability redouble the difficulty in selecting a satisfactory long-range nuclear energy strategy from the innumerable alternatives.

One outcome of the recent research on alternative technologies is that the LWR on the once-through uranium cycle has considerable latitude for future improvement in resource utilization. This paper will show that the LWR trend in fuel utilization is far from static and that the LWR, over its 17-year history since commercial introduction, has made sustained progress. Even more remarkable is that the evolutionary improvements in LWR fuel efficiency discussed in this paper are being realized in reactors designed and constructed in the period before the increase in uranium price in the mid-1970s.

The Department of Energy recognizes the important role the LWR will play in the long-range deployment of nuclear energy. A strong program has been instituted to assist in the continued improvement in LWR resource utilization efficiency, reliability, and safety. The goals of the improvement program are a retrofittable 15% reduction in uranium consumption by the late 1980s and research on systems that would realize as much as a 30% reduction by the end of year 2000. Successful completion of this ambitious program and other DOE initiatives such as advanced isotope separation would have a profound effect on long-range uranium consumption. Clear benefits accrue from reducing the pressure on uranium supplies by providing more time for developing positions on deployment of other advanced technologies and concomitant development and implementation of adequate safeguards against potential misuse of these technologies.

To reach the initial goal of a 15% reduction in fuel utilization, DOE is establishing a program based on utility/vendor cooperative efforts to extend fuel burnup from the current target of about 30,000 Mwd/mtU to the vicinity of 50,000 Mwd/mtU. Increased burnup, together with improved fuel management, and other improvements (e.g., modified lattice), should be adequate to meet the initial goal. The historical trends of LWR burnup shown in this report are not inconsistent with this goal if the fuel development program initiated by DOE is aggressively pursued with continued utility and vendor cooperation. Indications of substantial foreign interest in the U.S. programs may speed their development and enhance worldwide acceptability and implementation.

1.0 INTRODUCTION

The present study was performed for the U.S. Department of Energy, under Contract DE-AC-01-79ER10020, for the purpose of describing and assessing U.S. experience in fuel burnup and resource utilization over the past 16 years of light water reactor (LWR) power plant operation. The assessment is based on actual spent-fuel-unloading historical data for 55 plants from 1962 through the end of 1978. In assessing these data, some particular data points were eliminated in order that the results might be more representative of zirconium-clad UO_2 fuel assemblies typical of modern LWR technology.

Statistical analyses and calculations of resource utilization were made in an effort to describe historical trends. Any extrapolation should be made with great caution for several reasons, among which are the following.

- Few of the reactors have attained an equilibrium fuel cycle and — despite efforts to screen non-representative data — the data includes the approach-to-equilibrium fuel, especially for reactors started up in recent years.

- The current design "equilibrium" fuel cycles — 33,000 Mwd/mtU, 3.2% enrichment for PWRs and 27,300 Mwd/mtU, 2.72% enrichment for BWRs — are somewhat arbitrary and largely represent vendor warranties rather than any real limit to performance.

- Potential operating and licensing problems associated with improved fuel performance have not been fully evaluated, although programs are currently underway to investigate such factors.

- Historical fuel performance data inherently include various levels of vendor optimism, utility preferences in fuel management and changes in fuel element design/fabrication techniques.

- Extrapolation of fuel performance must consider factors other than historical performance, such as incentives, political/economic/social factors, and level of effort expended in seeking improved performance.

2.0 SUMMARY AND CONCLUSIONS

Over the past 16 years, there has been a continuous increase in average discharge fuel burnup, increasing from around 8000 Mwd/mtU in 1962 to 24,000 Mwd/mtU in 1978. Figure 2.1 illustrates the actual fuel burnup achieved in the various discharge batches, together with statistical trend lines derived by weighting the burnup by the amount of fuel in each discharged batch. Figures 2.2 and 2.3 show similar data for PWRs and BWRs, respectively. Screened data, selected to be more representative of zirconium-clad UO_2 fuel in current LWR reactors, are discussed in Section 5.

Current nominal design fuel burnups of 33,000 Mwd/mtU for PWRs and 27,300 Mwd/mtU for BWRs (see NUREG-0480) are somewhat arbitrarily designated, based largely on vendor warranties and utility fuel management policies. Although the data in Figs. 2.1-2.3 indicate that the average discharge fuel burnup has not yet achieved the current nominal design values, there are a number of discharge batches that have significantly exceeded these values, reaching, in one case, a discharge burnup of nearly 38,000 Mwd/mtU. It should be recognized that the data in Figs. 2.1-2.3 include startup fuel batches that have not yet attained the equilibrium fuel cycle, particularly among those reactors starting up in the last few years.

Since 1962, the design power level of reactors coming on line has increased substantially. Figure 2.4 illustrates the trend in reactor size with time, including reactors with projected startup dates through 1985.* At the present time (1979), the average reactor power is about 750 Mw(e) and is projected to increase to slightly over 900 Mw(e) by 1985. Visual examination of Fig. 2.4 suggests three groups of reactor sizes — greater than 1000 Mw(e), between 750 Mw(e) and 1000 Mw(e), and less than 750 Mw(e) — with an apparent increase in the number of larger plant sizes with time. Since the trend lines in Figs. 2.1-2.3 are weighted by the amount of fuel discharged, the larger size reactors will contribute more to the weighted average fuel burnup in a given year than the smaller reactors.

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* As compiled in the booklet Nuclear Power '79 published annually by, and available from, Southern Science Applications, Inc.

The larger reactors also utilize fuel more efficiently as a result of reduced neutron losses by leakage. Hence, increasing reactor size with time will result in improved fuel utilization.

Fuel burnup alone, however, does not completely represent trends in resource utilization, since it does not reveal the effect of fuel enrichment on U_3O_8 ore requirements. The efficiency of fuel utilization may be defined in terms of the total energy produced (Kwh) per pound of U_3O_8 ore, i.e.,

$$\text{(2.1)} \qquad \frac{\text{Kwh}}{\text{lb } U_3O_8} = 9.24 \times \epsilon \times B \times \frac{(.711 - E_T)}{(E - E_T)}$$

where ϵ is the net thermal efficiency of the plant, B is the fuel burnup in Mwd/mtU, E is the fuel enrichment in wt. percent U-235, and E_T is the tails enrichment. This function assumes a tails enrichment of 0.2% and neglects processing losses in U_3O_8 conversion and fuel fabrication.

Figures 2.5 and 2.6 illustrate the efficiency of fuel utilization, where the data points are the annual average efficiency of discharged fuel weighted by the amount of fuel in each discharge batch. As in the case of fuel burnup alone, these data also indicate an increasing efficiency of resource utilization with time and experience. Reasonably good correlation (coefficient = 0.851) with all the data is observed, although the correlation (coefficient = 0.951) is somewhat better using the screened data. Both linear and logarithmic statistical trends were calculated with equally good correlation, implying that time extrapolation cannot be made with any high degree of confidence. A distortion appears to exist around 1971-72 (Fig. 2.5), which may reflect the fuel densification problem that occurred in this time period.

The current data show an efficiency of fuel utilization of 15,200 Kwh/lb U_3O_8 (15,500 Kwh/lb U_3O_8 with screened data) in 1978, a significant increase over the ~6500 Kwh/lb U_3O_8 in 1962. Equation (2.1) above shows that the efficiency of fuel utilization will increase in direct proportion to the fuel burnup achieved, provided that there is no penalty due to a requirement for higher enrichment to maintain reactivity. For example, an increase to 50,000 Mwd/mtU burnup (at 4.5% enrichment)* would increase the fuel utilization to ~18,000 Kwh/lb U_3O_8. Using a 5-batch refueling scheme, allowing an

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* Studies of Alternative Nuclear Technologies, Report SSA-106, Southern Science Applications, Inc., April 1978.

enrichment of 4.1% to be adequate** for 50,000 Mwd/mtU in PWRs, the fuel utilization efficiency would increase to ~20,000 Kwh/lb U_3O_8. Thus, substantial improvements in fuel utilization efficiency are possible. A hypothetical upper limit of approximately 36,000 Kwh/lb U_3O_8 has been estimated on the basis of full use of all reactivity available (i.e., an idealized on-line refueling scheme) and prompt removal of xenon poisoning. On this basis, the average 1978 fuel utilization efficiency would be ~42% of the hypothetical limit and the current performance specification would represent ~47% of the hypothetical limit. Improvements resulting from the DOE fuel utilization improvement program could increase the efficiency to ~55% of the hypothetical limit by the late 1980s.

It is also interesting to note that increasing fuel burnup reduces the requirement for spent fuel storage. At the higher burnup, each fuel assembly will have produced proportionately more energy; consequently, for a given energy production, there is a reduction in the number of fuel elements to be stored. Although the fission product activity in each assembly will be higher, increasing fuel burnup from 33,000 Mwd/mtU to 50,000 Mwd/mtU in PWRs decreases spent fuel storage requirements by about 33%, or has the equivalent effect of increasing spent fuel storage capacity by about 33%.

Yet another measure of resource utilization may be developed by calculating the equivalent 30-year requirement for U_3O_8 (standard tons, normalized to a 1000 Mw(e) plant operating at a 75% annual load factor), using the initial enrichment and achieved burnup of each discharged batch. The normalized 30-year requirement for U_3O_8 is given by the following approximate relationship:

$$\text{(2.2)} \qquad \text{ST } U_3O_8^{\,30\text{ yr}} = 1.465 \times 10^6 \times \frac{(E-0.2)}{B} \times \left(45 + Y - \frac{Y}{N}\right)$$

where B and E have the same meaning as in equation (2.1) above, N is the number of fuel regions or batches normally in the core (nominally 3 for PWRs and 4 for BWRs), and Y is the fuel lifetime in years.

Figures 2.7 and 2.8 show the calculated equivalent resource requirements for all plants, with the data points representing the annual average values weighted by the amount

** N. L. Shapiro and Y. Liu, Improvement of Fuel Utilization for Once-Through PWR Cycles, Trans. Amer. Nucl. Soc., Vol. 30, pp 276-277, Nov. 1978.

of fuel in each discharge batch. Both linear and logarithmic trend lines are shown on Figs. 2.7 and 2.8. These data also show continued reduction in resource requirements from about 14,500 ST U_3O_8 in 1962 to less than 7000 ST U_3O_8 in 1978. Some discharge batches exceeded the current design expectations of 6250 ST U_3O_8 over a 30-year operating period.

Plutonium production in the fuel discharged over the past 16 years has also been estimated. To a first approximation, the fissile plutonium content is described by the following relationship:

$$\text{(2.3)} \qquad \text{Fissile Pu}, \frac{kg}{mtU} = (3.79 + .908E) \times \left(1-e^{-2.313 \times 10^{-4} B/E}\right)$$

where B and E have the same meaning as in equation (2.1) above.

On the basis of equation (2.3), the quantities of fissile plutonium produced are shown in Fig. 2.9. At the end of 1978, the total amount of fissile plutonium in spent fuel containing 4520 mtU is estimated to be approximately 22 metric tons. Figure 2.10 shows the average and cumulative average plutonium content in the discharged fuel.

Because of the relative insensitivity of plutonium content in discharged fuel to burnup, the total quantity of fissile plutonium can be projected on the basis of the anticipated installed nuclear generating capacity currently scheduled. Using the announced schedule for new nuclear generating capacity through 1990, the projected potential quantity of fissile plutonium is shown in Fig. 2.11, using both current fuel burnup specifications and assuming further increase in discharge burnup. This projection implies that a maximum of 200 to 250 metric tons of fissile plutonium would be available by 1990 in fuel containing an average of about 7 kg Pu per mtU. The total projected quantity of uranium in the discharged fuel, corresponding to the fissile plutonium production (Fig. 2.11) is shown in Fig. 2.12. Any effort to project beyond 1990 would be subject to considerable uncertainty, since such a projection inherently involves assumptions of installed nuclear capacity as well as extensive extrapolation of fuel performance.

3.0 DATA BASE

3.1 Fuel Operating Experience

The data base for the analyses consists of actual fuel discharges from 57 reactors (525 fuel discharge batches) as compiled by the Nuclear Assurance Corporation (FUEL-TRAC program) covering an operating period from 1962 through 1978. Table I lists the 55 reactors selected for analysis, including the plant startup date and certain other characteristic information. From these data and the reported refueling information, a computerized data file was developed,* together with a sorting routine that permitted selection of refueling data on several bases, averaging on an annual basis, and preparation of input data to an associated statistical analysis code for regression analyses.

In reviewing the base data, several batches of fuel were identified as atypical (e.g., experimental) or as having been removed prematurely for reasons unrelated to fuel perform-performance. These fuel batches (total of 41 batches) were eliminated from the data base. For example, in June 1973, four natural uranium fuel assemblies were removed from the San Onofre-1 reactor. Because of the atypical enrichment used (natural uranium), this batch was considered unrepresentative of fuel performance despite the relatively high burnup (24,000 Mwd/mtU) achieved. Similarly, the entire Vermont Yankee core was replaced prematurely in November 1974, apparently as an administrative decision (change in fuel design) unrelated to the potential performance of the fuel. In addition, Big Rock Point data (54 discharge batches) were eliminated because of the low power level (75 Mw(e)) and the fact that the reactor has been frequently used for experimental irradiations. Hence, the fuel enrichment would not be representative, although substantial fuel burnups (as high as about 28,000 Mwd/mtU) were reached. In the case of Elk River (thorium core), Humboldt Bay (63 Mw(e) BWR), and LaCrosse (48 Mw(e) BWR), as well as the Pathfinder, Bonus, the N.S. Savannah and other early demonstration/experimental reactors, no data on fuel discharges were available: in any case, the data would have been eliminated as unrepresentative.

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* A listing of the data file is available as a separate appendix to this report.

Table I REACTORS INCLUDED IN DATA COMPILATION

Name	Docket No.	Net Capacity Mw(e)	Total Production* 10^6Mwh(net)	Startup Date	mtU Discharged**
Arkansas Nuclear-1	313	836	19.0	1974	28.3
Beaver Valley-1	334	800	5.4	1976	24.0
Browns Ferry-1	259	1065	19.1	1974	41.9
Browns Ferry-2	260	1065	15.1	1975	25.9
Browns Ferry-3	296	1065	13.6	1977	7.5
Brunswick-2	324	790	10.3	1975	4.5
Calvert Cliffs-1	317	810	19.3	1975	54.9
Calvert Cliffs-2	318	810	10.4	1977	7.0
Connecticut Yankee	213	575	42.8	1968	157.2
Cook-1	315	1044	21.8	1975	58.0
Cooper Station	298	764	18.0	1974	54.7
Crystal River-3	302	797	6.0	1977	1.9
Dresden-1	10	197	15.5	1960	128.7
Dresden-2	237	772	31.0	1970	234.6
Dresden-3	249	773	27.5	1971	110.2
Duane Arnold	331	515	10.1	1975	51.4
Ft. Calhoun-1	285	457	13.1	1973	63.4
Ginna	244	470	24.2	1970	117.8
Hatch-1	321	717	13.7	1975	50.2
Indian Point-1	3	257	(NA)	1962	39.6
Indian Point-2	247	864	20.0	1974	89.3
Indian Point-3	286	965	13.6	1976	29.4
James FitzPatrick	333	800	14.2	1975	25.4
Kewaunee	305	517	15.2	1974	47.1
Maine Yankee	309	810	28.7	1972	135.7
Millstone-1	245	654	29.1	1970	136.8
Millstone-2	336	810	12.8	1975	28.4
Monticello	263	536	24.1	1971	140.9

Table I REACTORS INCLUDED IN DATA COMPILATION (Continued)

Name	Docket No.	Net Capacity Mw(e)	Total Production 10^6Mwh(net)*	Startup Date	mtU Discharged**
Nine Mile Point-1	220	610	28.5	1969	137.8
Oconee-1	269	860	23.8	1973	107.8
Oconee-2	270	860	19.8	1974	61.7
Oconee-3	287	860	21.1	1974	56.5
Oyster Creek	219	620	31.5	1969	160.0
Palisades	255	635	16.0	1971	139.6
Peach Bottom-2	277	1051	25.8	1974	84.5
Peach Bottom-3	278	1035	22.9	1974	49.7
Point Beach-1	266	495	25.4	1970	106.4
Point Beach-2	301	495	20.8	1972	53.6
Prairie Island-1	282	507	15.5	1973	47.3
Prairie Island-2	306	507	13.4	1974	47.7
Quad Cities-1	254	769	26.0	1972	112.7
Quad Cities-2	265	769	25.7	1972	101.6
Rancho Seco-1	312	913	15.6	1975	30.6
Robinson-2	261	665	31.0	1971	143.4
Salem-1	272	1079	7.8	1977	27.6
San Onofre-1	206	436	29.6	1968	114.3
Surry-1	280	775	24.8	1972	123.6
Surry-2	281	775	23.5	1973	110.2
Three Mile Island-1	289	776	21.8	1974	88.1
Turkey Point-3	250	666	23.3	1972	84.0
Turkey Point-4	251	666	20.0	1973	88.4
Vermont Yankee	271	504	17.6	1972	130.4
Yankee-Rowe	29	175	19.7	1961	140.3
Zion-1	295	1040	25.5	1973	83.7
Zion-2	304	1040	23.5	1974	28.9

* Taken from "Nucleonics Week," Dec. 28, 1978, corrected to net total (lifetime) electric energy production.

** Total quantity discharged through 1978.

Three plants — Brunswick-1, St. Lucie-1, and Trojan — were known to have operated during 1978, but apparently did not discharge any fuel. In addition, there is reason to believe that several early discharge batches from Browns Ferry-1 and -3, FitzPatrick, and Point Beach-2 were not included in the data base. These omissions do not affect materially the results of this study.

The remaining data base — 430 fuel discharge batches from 55 reactors — was used for the evaluation of trends in fuel burnup and resource utilization. The indices of performance for each discharge fuel batch were weighted by the amount of fuel (kg UO_2) in the batch to obtain the weighted annual averages. By 1978, the weighted average burnup in all the discharged fuel was approximately 22,000 Mwd/mtU.

For evaluating the total quantity of fissile plutonium produced, the entire data base of 525 discharge batches from 57 plants was used.

3.2 Screened Data and Criteria

In addition to evaluation of the fundamental data base described above, an effort was made to screen out those fuel discharge batches that represented initial low-enrichment startup fuel batches or other special circumstances, in order that the remaining "screened" data would more nearly be representative of performance in zirconium-clad LWR fuel under approximately equilibrium conditions. To a large extent, screening the data inherently involves a considerable degree of judgement. However, several criteria for screening out fuel batches were established as follows.

- Eliminate all fuel batches that were scheduled for re-insertion in a subsequent cycle for further irradiation;
- eliminate low-enrichment and/or low-burnup fuel assemblies that appear to be part of the initial startup cycle;
- eliminate intermediate enrichment fuel assemblies where the burnup achieved appeared to indicate they were part of the first startup cycle; i.e., those whose burnup-to-enrichment ratio was less than about 6000 Mwd/mtU per percent U-235 enrichment; and

— discard data from fuel batches discharged at unusually-low burnup values, indicative of premature discharge for reasons unrelated to fuel performance (e.g., possible planned re-insertion, administrative decisions, or changes in fuel management philosophy).

Initially, it was thought desirable to eliminate discharge batches with stainless-steel-clad fuel (from the San Onofre, Yankee-Rowe, and Connecticut Yankee reactors). However, this would result in the elimination of all of the early PWR burnup data. Furthermore, the burnup — but not fuel enrichment — would still likely be a valid measure of fuel performance. In order to salvage this early PWR experience, the stainless-clad fuel was included in the analyses, but with an approximate correction applied to the enrichment of stainless-clad fuel to normalize fuel utilization efficiency and resource requirements to equivalent zirconium-clad fuel. This correction consisted of reducing the actual enrichment by 0.8% U-235. In some cases, analyses were made both with and without the stainless-clad fuel data.

Application of the screening criteria resulted in the elimination of some 175 data points, leaving a total of 255 fuel discharge batches from 47 reactors as the screened data base. Table II lists the number of fuel discharge batches and reactors in the data base for the evaluation of trends.

Table II NUMBER OF FUEL BATCHES AND REACTORS IN DATA BASE

Case	Number of Fuel Batches	Number of Reactors
All plants	430	55
All plants, screened data	255	47
PWR	274	33
PWR, screened data	176	28
BWR	156	22
BWR, screened data	79	19

3.3 Statistical Analysis

The sorting routine developed in conjunction with the data base permitted selecting data on the basis of reactor type and nature of data desired (screened or unscreened).

In the sorting process, weighted annual average parameters were calculated, weighting each discharge fuel batch by the amount of fuel (kg UO_2) contained in the discharge batch. These weighted annual average parameters (burnup, fuel utilization efficiency, and 30-year resource utilization) were then supplied as input to a linear regression analysis code for least-squares fitting and calculation of the correlation coefficient. The regression analysis code also contained an exponential fitting option that was utilized in some evaluations. In addition, the sorting-averaging routine for processing the data base calculated the standard deviation of the individual fuel discharge parameters for each year (provided there was more than a single discharge batch in the given year).

In general, there was little difference in correlation coefficients for the exponential and linear regression fits to the data, attributable more to scatter in the data than to theoretical validity. In either event, the regression fitting tended to smooth out the perturbation in the early 1970s — apparent on visual examination of the plots — resulting from the known fuel densification problem.

3.4 Learning Theory

In addition to determining the time-dependent statistical trends, a correlation with cumulative fuel throughput was sought. This correlation, derived from learning theory, is based upon the total quantity of fuel processed, with a constant improvement expected for each doubling in throughput. In our case the throughput quantity is the cumulative kilograms of all fuel discharged. A learning curve correlation was not attempted with fuel burnup, since the effect of enrichment would not be included. Also, because of the more limited data base, a learning curve correlation was not made on screened data.

4.0 ANALYTICAL FORMULATIONS

4.1 General

In assessing the history of fuel performance in commercial U.S. light water reactors, burnup alone does not provide an adequate index of performance. Two other indices have been developed to include the effect of fuel enrichment on raw material resource requirements — (1) fuel utilization efficiency in Kwh/lb U_3O_8 and (2) the 30-year U_3O_8 requirements (resource utilization) normalized to a 1000 Mw(e) plant operating at a 75% capacity factor. The latter index is calculated as if each discharge batch were the equivalent of equilibrium operation for 30 years. All three indices of fuel performance are considered in the statistical treatment of the historical data. In addition, the approximate fissile plutonium production has been calculated and the results are given in subsequent sections of this report.

4.2 Fuel Utilization Efficiency

The expression for fuel utilization efficiency in Kwh/lb U_3O_8 has been developed from conversion of units and the mass balance from natural uranium through the enrichment process. This expression,

$$(4.1)\quad \frac{\text{Kwh}}{\text{lb } U_3O_8} = B\left(\frac{\text{Kw(t)D}}{\text{kg U}}\right) \times \epsilon \left(\frac{\text{Kw(e)}}{\text{Kw(t)}}\right) \times 24\left(\frac{\text{hr}}{\text{D}}\right) \times 0.848\left(\frac{\text{kg U}}{\text{kg } U_3O_8}\right)$$

$$\times\ 0.4536\left(\frac{\text{kg}}{\text{lb}}\right) \times \left(\frac{0.711-E_T}{E-E_T}\right)$$

$$= 4.717\ \epsilon \times B/(E-0.2),$$

assumes a tails enrichment of 0.2 and neglects processing losses in conversion of U_3O_8, enrichment and fuel element fabrication. The factor $(0.711-E_T)/(E-E_T)$ is the product to feed ratio required (by mass balance) in the enrichment process, which, for 0.2% tails enrichment (E_T) is 0.511/(E-0.2). In this expression, B is the fuel burnup in Mwd/mtU (or Kw(t)D/kg), ϵ is the net thermal efficiency of the plant and E is the fuel enrichment in weight percent U-235. Current design characteristics of LWRs (33,000 Mwd/mtU at 3.2% enrichment for PWRs and 27,300 Mwd/mtU at 2.7% enrichment for BWRs) results in approximately 17,000 Kwh/lb U_3O_8.

Higher fuel burnup would increase the fuel utilization efficiency in direct proportion, provided there was no associated enrichment increase necessary for reactivity requirements. Some enhancement in fuel utilization is possible with increased burnup, since the enrichment does not increase proportionately, particularly if a larger number of refueling batches are used in the core. For example, it has been suggested* that a burnup of 50,000 Mwd/mtU is possible in a 5-batch core using an enrichment of approximately 4.1% U-235. This would yield a fuel utilization efficiency of about 20,000 Kwh/lb U_3O_8.

Independent calculations of the reactivity lifetime achievable with 3.2% enriched fuel, with no loss of reactivity to control poisons or to xenon, indicate a burnup of as much as 70,000 Mwd/mtU could possibly be attained under these hypothetical conditions (in effect, an idealized on-line refueling scheme with immediate removal of all xenon as it is produced). Fuel utilization efficiency for this hypothetical upper limit case would be approximately 36,000 Kwh/lb U_3O_8. Thus, current design specifications for LWR plants (17,000 Kwh/lb U_3O_8) are approximately 47% of the hypothetical upper limit.

4.3 Resource Utilization

Resource utilization is defined (for consistency in comparison to other studies) as the total quantity of U_3O_8 required by a plant over a 30-year lifetime, normalized to a 1000 Mw(e) plant operating at an average of 75% capacity factor.

The burnup of the fuel, B, is the quantity of thermal energy the fuel has produced per metric ton of heavy metal, and the burnup times the thermal efficiency of the plant, E, determines the amount of electric energy the fuel produces. The amount of fuel required annually to produce a Gw(e)-yr of energy is then

$$\frac{1000\ \frac{\text{Mw}}{\text{Gw(e)}} \times 365\ \frac{\text{days}}{\text{yr}}}{B\ \frac{\text{Mw(th) days}}{\text{mtU}} \times \frac{\text{Mw(e)}}{\text{Mw(th)}}} \quad (4.2)$$

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* N.L. Shapiro and Y. Liu, Improvement of Fuel Utilization for Once-Through PWR Cycles, Trans. Amer. Nucl. Soc., Vol. 30, pp 276-277, Nov. 1978.

To determine the amount of U-235 required annually, I, the above quantity must be multiplied by the plant capacity factor, C, and the enrichment of U-235 in the heavy metal, E. So,

$$I = 3560 \frac{C \times E}{B \times \epsilon} = \frac{mtU^{235}}{Gw(e)\text{-}yr} ,$$

where C is the plant capacity factor (fraction),

E is the enrichment of the heavy metal (%),

B is the fuel burnup in Mwd/mtU, and

ϵ is the net thermal efficiency (fraction).

The total weight of U_3O_8 required to supply I mtU^{235} per year is (in standard tons),

$$(4.3) \qquad \frac{ST\ U_3O_8}{Gw(e)\text{-}yr} = 130 \frac{I}{E} \times \frac{E-E_T}{0.711-E_T} ,$$

where E_T is the tails enrichment. The factor $(E-E_T)/(0.711-E_T)$ is the feed to product ratio required in the enrichment process (by mass balance). Substituting equation (4.2) yields

$$(4.4) \qquad \frac{ST\ U_3O_8}{Gw(e)\text{-}yr} = 4.745 \times 10^5 \times \frac{C}{B \times \epsilon} \times \frac{E-E_T}{0.711-E_T} .$$

If all fuel cycles were equilibrium, the 30-year resource requirement (ST U_3O_8) would be 30 times the value in equation (4.4) above. However, the initial core loading is not at equilibrium, and correction for this must be included. One method of approximating the initial core loading is to assume each of N regions of a multi-region core is loaded with fuel of U^{235} content simulating the equilibrium core. Other methods of initially loading the core and approaching the equilibrium fuel cycle would be envisioned, but the overall penalty in resource utilization will not be likely to differ greatly from the simple approximation used here. Assuming a linear decrease with burnup from the initial region (I/N) to the average discharge (F/N) from each region, the initial core loading is

$$\sum_{n=1}^{N}\left[(I-F)\times\frac{n}{N}+F\right]=\frac{I-F}{N}\times\sum_{n=1}^{N}n+NF \tag{4.5}$$

$$=\tfrac{1}{2}\left[I(N+1)+F(N-1)\right].$$

The effective number of annual loadings required for the initial loading is.

$$\frac{Y}{N}\left[\frac{I(N+1)+F(N-1)}{2I}\right], \tag{4.6}$$

where Y is the fuel operating lifetime in years. Hence, the total number of effective annual loads for the 30-year resource requirement becomes

$$30-\frac{Y}{N}+\frac{Y}{N}\left[\frac{I(N+1)+F(N-1)}{2I}\right]. \tag{4.7}$$

Multiplying the annual resource requirement — equation (4.4) — by the total number of effective annual loads (4.7), the 30-year resource requirement becomes

$$\text{ST } U_3O_8^{\,30\text{ yr}}=4.745\times10^5\times\frac{C}{B\times\epsilon}\times\left(\frac{E-E_T}{0.711-E_T}\right) \tag{4.8}$$

$$\left\{30-\frac{Y}{N}+\frac{Y}{N}\left[\frac{I(N+1)+F(N-1)}{2I}\right]\right\}.$$

Equation (4.8) may be simplified* by making several approximations appropriate for modern LWRs, as follows:

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* Equation (4.8) (simplified) for on-line refueling (e.g., CANDU-type reactors) becomes approximately

$$\text{ST } U_3O_8^{\,30\text{ yr}}=4.64\times10^5\times\frac{E-0.2}{\epsilon\times B_T}\times(45+Y).$$

For thorium containing cores, equation (4.8) becomes approximately

$$\text{ST } U_3O_8^{\,30\text{ yr}}=4.64\times10^5\times\frac{E-0.2}{\epsilon\times B}\times\frac{E'}{E}\times\left(45+Y-\frac{Y}{N}\right),$$

where E' is the % U-235 per unit weight of heavy metal including thorium.

— capacity factor, C = 0.75;

— tails enrichment, E_T = 0.2;

— net plant efficiency = 0.317; and

— discharge U-235 content = 1/3 I.

Then equation (4.8) reduces to

$$\text{(4.9)} \qquad \text{ST } U_3O_8^{\;30\ yr} = 1.463 \times 10^6 \times \frac{E-0.2}{B} \times \left(45 + Y - \frac{Y}{N}\right).$$

This function (4.9) was used to estimate the equivalent 30-year resource requirement for the various discharge fuel batches in the reference data base. For the current performance specifications of LWRs, the 30-year U_3O_8 requirement becomes 6250 ST for PWRs (N=3) and 6480 for BWRs (N=4).

It may be noted that the expression for resource utilization does not account for the final fuel cycle at end of reactor life (30th year). Although not strictly correct, it is consistent with practice in the literature and is probably reasonable for relative comparison of fuel cycles. Furthermore, reactor lifetime may well exceed 30 years (e.g., 40 years has been used in some studies) and it would be premature to define exactly how the final fuel cycle may be handled in the future. Unless the residual energy in the final fuel cycle were to be salvaged, the effect would be to increase the amount of U_3O_8 required over the reactor lifetime and thus tend to offset the advantage that might otherwise be achieved by increased fuel burnup.

4.4 Plutonium Production

Plutonium is inherently produced in reactors operating on the U-235/U-238 fuel cycles, being produced at a nearly constant rate (for a given power level) and consumed in-situ at a rate dependent upon the amount present. The in-situ burning of plutonium contributes significantly to the amount of energy produced by the fuel, particularly at higher fuel burnups. If irradiation were continued sufficiently long, the rate of consumption would approach the rate of production and the plutonium concentration in the fuel would eventually reach a saturation or equilibrium value that depends upon the reactor design characteristics and the initial fuel enrichment. Although the detailed phenomena of plutonium production and consumption are complex, examination of a number of specific reactor calculations indicates that the approach to equilibrium is approximately exponential in character. This fact allows derivation of a simple approximation to describe the burnup-dependent concentration of plutonium in the fuel of current LWR concepts.

Examinations of numerous burnup-dependent fissile plutonium concentrations in modern LWR designs permitted the specification of an empirical fit of the following form:

$$\text{Fissile Pu, kg/mtU} = (0.908E + 3.79) \times \left(1 - e^{-2.313 \times 10^{-4} B/E}\right).$$

Although this function is only approximate (probably within ± 10%), it is useful in providing an estimate of the total amount of fissile plutonium and approximate concentrations in the discharged fuel. In reactors operating to the current performance specifications, the fissile plutonium content in discharged fuel is 6.26 kg/mtU for PWRs and 5.82 kg/mtU in BWRs.* In a PWR operating to higher burnup (50,000 Mwd/mtU), the fissile plutonium content at discharge would be 7.2 kg/mtU for 4.1% initial enrichment and 7.46 kg/mtU at 4.5% initial enrichment.

For the current performance specifications of modern LWRs, the fissile plutonium production can be related to U_3O_8 requirements and becomes about 0.8 kg fissile Pu/ST U_3O_8 for PWRs and about 0.9 kg fissile Pu/ST U_3O_8 for BWRs. The net quantity of plutonium produced will increase slightly with increasing burnup, but decrease significantly with increasing enrichment. For example, at 50,000 Mwd/mtU burnup and 4.1% enrichment, the plutonium production in a modern PWR would be reduced to around 0.7 kg fissile Pu/ST U_3O_8, while the fissile plutonium content in the discharged fuel would increase from 6.26 kg/mtU to 7.2 kg/mtU.

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* NUREG-0480 estimates 6.5 kg/mtU for PWRs and 5.6 kg/mtU for BWRs.

5.0 HISTORICAL TRENDS AND EVALUATION

5.1 Trends in Fuel Burnup

From 1962 to 1978, the annual average discharge fuel burnup in all U.S. LWRs increased from approximately 8000 Mwd/mtU to approximately 22,000 Mwd/mtU. Figure 5.1 shows the annual average burnup (burnup in each discharge batch weighted by the quantity of fuel in the batch) and the statistical trend line (linear least-squares fit). Using screened data (Sec. 3.2), the fuel burnup history shown in Fig. 5.2 also shows consistent improvement in burnup achieved, increasing from around 14,000 Mwd/mtU in 1969 to around 25,000 Mwd/mtU in 1978. The screened data, with initial startup fuel batches eliminated, more nearly represent equilibrium fuel cycle operation, although some influence of early core operation is undoubtedly present.

Figures 5.3-5.6 show the data individually for BWRs and PWRs. As expected, PWR fuel has attained, on the average, a higher fuel burnup than BWR fuel, although the slopes of the trend lines are not greatly different. Linear projection of the trend lines implies that both types of reactors should attain burnup specifications at approximately the same time.

Current specifications of fuel burnups are derived largely from vendor warranties, and no inherent limit in achievable burnup is evident. However, projections of future discharge fuel burnup should be made with caution, since (1) the present data includes discharge fuel in the startup cycle which is not at equilibrium, and (2) increased fuel burnup in the years ahead depends upon the incentives that now exist or that may be created by government development programs, rising uranium ore costs, or spent fuel storage limitations.

Despite the uncertainty introduced by attempting to extrapolate fuel burnups, two possible scenarios are given in Fig. 5.7 — one based on a simple linear extrapolation of historical trend lines to current performance specifications, and a second based on accelerated improvements in fuel burnup, targeting an average discharge fuel burnup of 47,000 Mwd/mtU by 1990 (50,000 Mwd/mtU in PWRs and 41,000 Mwd/mtU in BWRs). The accelerated extrapolation is intended to take into consideration the DOE fuel utilization improvement program, and both extrapolations serve to illustrate bounding conditions in subsequent evaluations of potential trends in plutonium accumulation (Sec. 5.4).

Historically, the average increase in fuel burnup in all reactors has been approximately 920 Mwd/mtU per year, extrapolated to reach current performance specifications by about 1988. To accelerate fuel burnup improvement to attain a mean of 47,000 Mwd/mtU by 1990, it will be necessary to slightly more than double the historical rate of improvement (to about 2100 Mwd/mtU per year).

5.2 Trends in Fuel Utilization Efficiency (Kwh/lb U_3O_8

The quantity defined here as fuel utilization efficiency (Kwh/lb U_3O_8) includes the effect of fuel enrichment, using the function described in Section 4.2. Fuel utilization efficiency increases with increasing discharge fuel burnup but decreases with increasing enrichment. Figures 2.5 and 2.6, described previously, show the trend in net fuel utilization for all reactors since 1962 and reveal a generally consistent trend toward higher efficiency with time. In this case, both a linear and an exponential statistical fit were made, with approximately equal correlation coefficients.

Current performance specifications (33,000 Mwd/mtU at 3.2% enrichment for PWRs and 27,300 Mwd/mtU at 2.72% enrichment for BWRs) indicate essentially the same fuel utilization efficiency for BWRs (17,400 Kwh/lb U_3O_8) and for PWRs (16,800 Kwh/lb U_3O_8). The small difference is not of practical significance in the current generation of LWRs. The time-dependent efficiency for BWRs and PWRs is shown in Figs. 5.8 through 5.11, where the data points are the annual average values weighted by the quantity of fuel in each discharge batch. In each illustration, both a linear and an exponential statistical correlation are shown, with little difference in the correlation coefficients.

Fuel utilization efficiency is probably the most meaningful index of fuel performance among the three indices given in this report. Because startup fuel batches that operate to a lower burnup usually also have a lower enrichment (at least for PWRs), the efficiency index is less sensitive to distortion due to startup than fuel burnup alone. Although both BWRs and PWRs showed consistent improvement in efficiency with time, neither had attained current design specifications, on the average, by the end of 1978. Nevertheless, the current performance specification was reached or exceeded in a number of fuel discharge batches, as revealed in Fig. 5.12, which shows the actual unweighted data points. Future improvements in fuel performance can be expected to increase the fuel utilization efficiency. It has recently been suggested* that a fuel burnup of 50,000 Mwd/mtU be achieved in a 5-batch core requiring an enrichment of 4.1% U-235. This improvement could increase the fuel utilization efficiency to nearly 20,000 Kwh/lb U_3O_8.

5.3 Trends in Resource Utilization

Resource utilization is defined as the equivalent 30-year requirement for U_3O_8 in standard tons, normalized to a 1000 Mw(e) plant operating at 75% capacity factor. To display trends, resource utilization was calculated for each discharge batch as if the batch was representative of equilibrium discharge. As an index of reactor performance, resource utilization does not differ greatly from fuel utilization efficiency. It does, however, include the effect of the initial loading and startup fuel cycles, and was calculated to illustrate the improvement trend and for convenience in projecting gains.

Figures 2.7 and 2.8 (given previously) show the calculated equivalent resource utilization for all plants (weighted annual average), using both screened and unscreened data. In these illustrations, it is evident that current design specifications have not yet been met, though the general trend shows continuing improvement and approaches to the specifications. Considering scatter in the data, no significant difference between PWRs and BWRs was observed.

5.4 Trends in Fissile Plutonium Production

An estimate of the fissile plutonium in fuel discharged from operating plants, calculated by the relationship described in Section 4.4, has been presented previously in Fig. 2.9. These estimates, derived from the total data

* N. L. Shapiro and Y. Liu, Improvement of Fuel Utilization for Once-Through PWR Cycles, Trans. Amer. Nucl. Soc., Vol. 30, pp 276-277, Nov. 1978.

base of 525 discharge batches for 57 plants, indicate that, at the end of 1978, there was a total of 4520 metric tons of uranium containing approximately 22 metric tons of fissile plutonium in the discharged fuel. The present average concentration of fissile plutonium is 4.88 kg Pu/mtU. Figure 2.10 shows the concentration of plutonium in the discharged fuel has increased from 3.1 kg Pu/mtU in 1962 to 5.4 kg Pu/mtU in the fuel discharged during 1978. At the current fuel performance specification, the plutonium concentration in discharged fuel would be 6.3 kg Pu/mtU for PWRs and 5.8 kg Pu/mtU for BWRs. If the burnup in PWRs is increased to 50,000 Mwd/mtU (at 4.1% initial enrichment), the fissile plutonium concentration would be about 7.2 kg/mtU in the discharged fuel.

Projections of the maximum fissile plutonium production to the year 1990 have been made on the basis of currently-announced plans for nuclear power plant construction. Beyond 1990, the quantities of fissile plutonium stockpiled in spent fuel would be affected by future plans for as-yet-announced plants, and any attempt to project beyond 1990 would be subject to considerable uncertainty. Based upon currently-operating plants and those with announced schedules for construction, the total installed nuclear capacity in 1990 is expected to be about 195,000 Mw(e). Projections of plant operation beyond 1978 require assumptions of representative capacity factors. For this estimate, the assumptions* in the Generic Environmental Impact Statement, DOE 1559 (Draft) for capacity factor were used. In addition, two fuel burnup projections were assumed — (1) average burnup continues to increase linearly according to the statistical fit in Fig. 5.1, and (2) average burnup increases linearly from 22,000 Mwd/mtU in 1978 to

* "Each plant is assumed to start at 40% capacity, increase to 70% in the fourth year, operate at 70% for 22 years and then decline linearly until the plant shuts down at 40% capacity in its fortieth year."

47,000 Mwd/mtU in 1990 (average of 50,000 Mwd/mtU in PWRs and 41,000 Mwd/mtU for BWRs).* The resulting extrapolation of fissile plutonium production shown in Fig. 2.11 indicates that 200 to 250 metric tons of plutonium could be available in 1990 if announced schedules for nuclear plant construction remain valid.

5.5 Learning Curve Correlations

An alternate means of depicting resource utilization data, shown in Figs. 5.13 and 5.14, is to plot the data against the cumulative total of fuel discharged. To determine learning theory correlation, the annual fuel performance data for all plants was analyzed. Stainless steel data were also included, using the enrichment correction described earlier. Data points were ordered chronologically, in increments of 100,000 kg of fuel. Mass-averaged efficiency and utilization were then correlated to cumulative kg of fuel on a log-log graph. According to theory, data thus plotted should be fit by a straight line, with a slope showing 10-20% improvement in performance with each doubling in kg of fuel discharged.

When efficiency is plotted on this basis, good correlation is obtained, as shown in Fig. 5.13. This analysis indicates an 88% learning curve, which falls within the normal range of learning coefficients, and indicates that each subsequent doubling in uranium throughput will result in approximately a 12% improvement in efficiency. At the current rate of throughput, another 12% improvement to 17,000 Kwh/lb U_3O_8, can be expected by 1982. Thus, the current design specification for LWR fuel efficiency is demonstrated to be within near-term reach. Within the accuracy of this analysis, consistent results are obtained for fuel utilization (Fig. 5.14). For utilization, a 90% learning curve was obtained.

* Approximately 67% PWRs and 33% BWRs.

6.0 IMPLICATIONS FOR PROJECTED LWR IMPROVEMENTS

6.1 LWR Fuel Utilization Improvement Program

The existing DOE fuel utilization improvement program anticipates achieving a near term, retrofittable 15% reduction in the 30-year resource requirements for U_3O_8 in current LWRs, with further improvements in years ahead. This initial 15% improvement in resource utilization is expected to be achieved by a combination of (1) higher fuel burnup (50,000 Mwd/mtU in PWRs), (2) increased regionalization (number of batches or regions) in the core, (3) improvements in fuel management to reduce neutron losses, (4) and other improvements such as modified lattice. Achieving this by 1990 would appear to be a reasonable objective requiring that the historical rate of burnup increases be approximately doubled. In addition, increased fuel burnup will reduce spent-fuel storage requirements and result in greater energy recovery from in-situ burning of plutonium, with a consequent reduction in quantities of fissile plutonium remaining per unit of energy produced.

6.1.1 Effect of Increased Fuel Burnup

Examination of equations (2.1) and (2.2) reveals that fuel utilization efficiency varies directly, and 30-year U_3O_8 resource utilization varies inversely, with the fuel burnup achieved. However, increased enrichment is necessary to maintain reactivity and the improvement in fuel utilization efficiency as a result of increased burnup is offset by the increased enrichment requirement. Calculations of the enrichment necessary in a PWR for a fuel burnup of 50,000 Mwd/mtU result in 4.5% enrichment, if the current three batch (or region) refueling operation is maintained. This increase in fuel burnup to 50,000 Mwd/mtU in PWRs would result in a 5.7% increase in fuel utilization efficiency (Kwh/lb U_3O_8) and a similar 5.7% decrease in the 30-year U_3O_8 resource requirement. Fuel residence time (and refueling interval) is also increased in proportion to the increase in fuel burnup, providing there is no change in the average capacity factor.

6.1.2 Effect of Increased Fuel Regionalization

Increasing the number of fuel regions in the reactor core will allow a higher burnup to be achieved with a smaller penalty due to increased enrichment. Thus an increase in burnup (PWR) to 50,000 Mwd/mtU would require an enrichment of 4.1% U-235 if a 5-region core were used, rather than the 4.5% enrichment necessary with a 3-region core. For this performance specification, a 16.5% increase in fuel utilization efficiency (Kwh/lb U_3O_8) or an 11% reduction in the 30-year U_3O_8 resource requirement is possible.

The improvement in resource utilization (30-year U_3O_8 requirements) is less than for fuel utilization efficiency (Kwh/lb U_3O_8) because of the greater impact of the initial core loading during approach to equilibrium operation. This is reflected in the term (44 + N) in the numerator of equation (2.2) which tends to offset the improvement in resource utilization that might otherwise be achieved by higher burnup and a greater degree of regionalization.

6.1.3 Effect of Improved Fuel Management

Increasing the number of refueling regions in the core must also account for effects on power distribution, which will likely necessitate a different fuel management scheme than for the 3-region core. By carefully selecting the fuel management scheme to minimize neutron leakage from the outer radial boundary of the core, it may be possible to achieve additional reduction in U_3O_8 resource requirements. Combustion Engineering* has estimated that an additional savings of approximately 3% in resource requirements can be achieved by alternate fuel management strategies. Thus, a total of around 14% savings in the 30-year requirement for U_3O_8 can possibly be achieved with fuel operating to 50,000 Mwd/mtU in a 5-batch core.

6.2 Effect of Reactor Size

In an operating power reactor, an appreciable fraction of neutrons is lost by leakage. Because of the intentional (and necessary) effort to flatten the radial power distribution, the fraction of neutrons lost in the radial direction is greater than would be the case in a similar-size, unflattened reactor. Since leakage is proportional to surface-to-volume ratio, increasing reactor

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* N. L. Shapiro, Improvements in the Once-Thru PWR Fuel Cycle, Interim Progress Report for FY 1978, Report CEND-367, Combustion Engineering, Inc., January 1979.

size should result in reduced radial neutron leakage and improved resource (U_3O_8) utilization, provided there is no change in the relative radial power distribution. Calculations were made of the resource utilization requirements for various radii PWR cores (1-dimensional radial calculations at constant axial height), assuming that a fuel management scheme could be devised to maintain the same relative radial power distribution. The enrichment required for the same discharge fuel burnup (33,000 Mwd/mtU) was determined and used to estimate the 30-year requirement for U_3O_8. Figure 6.1 shows the percent change in resource utilization normalized to an 870 Mw(e) PWR. BWR cores are assumed to follow the same trend as PWRs, despite the difference in core power density. The small advantage (~3.6%) in BWR fuel utilization efficiency (Sec. 5.2) appears consistent with this assumption.

As indicated in Fig. 2.4, the average size of reactors has generally been increasing over the past 16 years, with plants reaching an average of over 700 Mw(e) in 1978. Furthermore, new plants scheduled to begin operation after 1978 generally tend to be of the larger sizes, with the majority exceeding 1000 Mw(e). By 1985, the average, existing reactor power level is projected to exceed 900 Mw(e). Beyond 1985, the average reactor power level should continue to increase, with the attendant improvement in U_3O_8 resource utilization.

6.3 Effect on Spent Fuel Storage Requirements

Increasing fuel burnup decreases proportionately the requirement for spent fuel storage capacity: i.e., an increase from the currently specified burnup of 33,000 Mwd/mtU for PWRs to 50,000 Mwd/mtU reduces spent fuel storage requirements by 33%. Each fuel assembly at the higher burnup will have produced proportionately more energy, and Fig. 6.2 illustrates the relative reduction in spent fuel storage requirements as a result of increased fuel burnup.

With increasing fuel burnup, the fission product inventory of long-lived radioactivity in each assembly will also be increased. Several ORIGEN code calculations were made to investigate the fission product and actinide inventories in PWRs at two different fuel burnup values (33,000 Mwd/mtU and 50,000 Mwd/mtU). Results of these calculations (Fig. 6.3) show that, although the activities for the two burnups are nearly equal immediately after shutdown (dominated by the short-lived saturated activities), the higher-burnup fuel contains more activity after a 5-year cooling period. In terms of activity per Kwh generated, however, the activities are very nearly equal after a 5-year cooling period, as shown in Table III. Thus, a 51% increase in fuel burnup results in a 47% increase in long-lived radioactive inventory in the spent fuel, but approximately equal activities in mC/Kwh.

6.4 Other Potential Improvements

A number of other methods of improving fuel utilization have been suggested in the literature. Most of these depend upon improvements in fuel management so as to maximize the achievable burnup for a given fuel enrichment. As shown by the analytical functions for fuel utilization efficiency.

$$\frac{\text{Kwh}}{\text{lb } U_3O_8} = 4.717 \times \frac{\epsilon \times B}{E-0.2}, \qquad (6.1)$$

or for the 30-year U_3O_8 utilization,

$$\text{ST } U_3O_8^{\,30\text{ yr}} = 4.644 \times 10^5 \times \frac{E-0.2}{\epsilon \times B} \times \left(45 + Y - \frac{Y}{N}\right), \qquad (6.2)$$

increases in fuel burnup for the same enrichment (or reduced enrichment for the same burnup) result in improved fuel utilization. In addition to improvements discussed in Sec. 6.1, other potential mechanisms for improving fuel utilization include the following.

- increased plant thermal efficiency;
- reducing, where possible, parasitic neutron losses in fission products (e.g., xenon-releasing fuel);
- further reduction in neutrons lost to leakage;
- reduced parasitic loss of reactivity due to materials of construction;
- reduced neutron losses to control poisons, accomplished by revised fuel management;

TABLE III CALCULATED RADIOACTIVITIES IN FUEL OF DIFFERING BURNUP

Cooling Time, Years	ACTINIDES				FISSION PRODUCTS			
	Curies/mtU		mC/Kwh		Curies/mtU		mC/Kwh	
	33,000 Mwd/mtU	50,000 Mwd/mtU	33,000 Mwd/mtU	50,000 Mwd/mtU	33,000 Mwd/mtU	50,000 Mwd/mtU	33,000 Mwd/mtU	50,000 Mwd/mtU
0	4.1×10^7	4.21×10^7	164	110	1.58×10^8	1.54×10^8	629	402
0.5	9.4×10^4	1.44×10^5	.38	.38	4.1×10^6	4.7×10^6	16.4	12.3
1.0	8.6×10^4	1.29×10^5	.34	.34	2.3×10^6	2.8×10^6	9.2	7.4
2.0	7.8×10^4	1.15×10^5	.31	.30	1.3×10^6	1.6×10^6	5.0	4.3
3.0	7.4×10^4	1.09×10^5	.30	.28	8.1×10^5	1.1×10^6	3.2	2.9
5.0	6.8×10^4	9.95×10^4	.27	.26	4.9×10^5	7.2×10^5	2.0	1.9

— increased reactivity by increased moderation in the core;

— recovery of residual burnup remaining in the startup fuel batches;

— more uniform fuel burnup, allowing a higher average burnup to be achieved; and

— utilizing, where possible, moderator-temperature reactivity effects and reduced xenon poisoning at lower power.

Of these, increasing plant thermal efficiency and decreasing fission product poisoning afford the largest potential gains. An increase in thermal efficiency from 33% to 35%, for example, would reduce U_3O_8 resource requirements by about 6%, while an increase to 38% efficiency could accomplish an improvement in resource utilization of around 13%.

Previous estimates* of the effect of xenon poisoning indicate that a reduction in U_3O_8 resource requirements as large as 16% could possibly be achieved if the poisoning and excess reacitvity margin used to control xenon could be eliminated. The remaining mechanisms for improving fuel utilization vary greatly in their effectiveness and in the degree of difficulty of implementation.

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* Survey of the Current Status of the LWR and Projected Improvements, Report SSA-117, Southern Science Applications, Inc., December 1978.

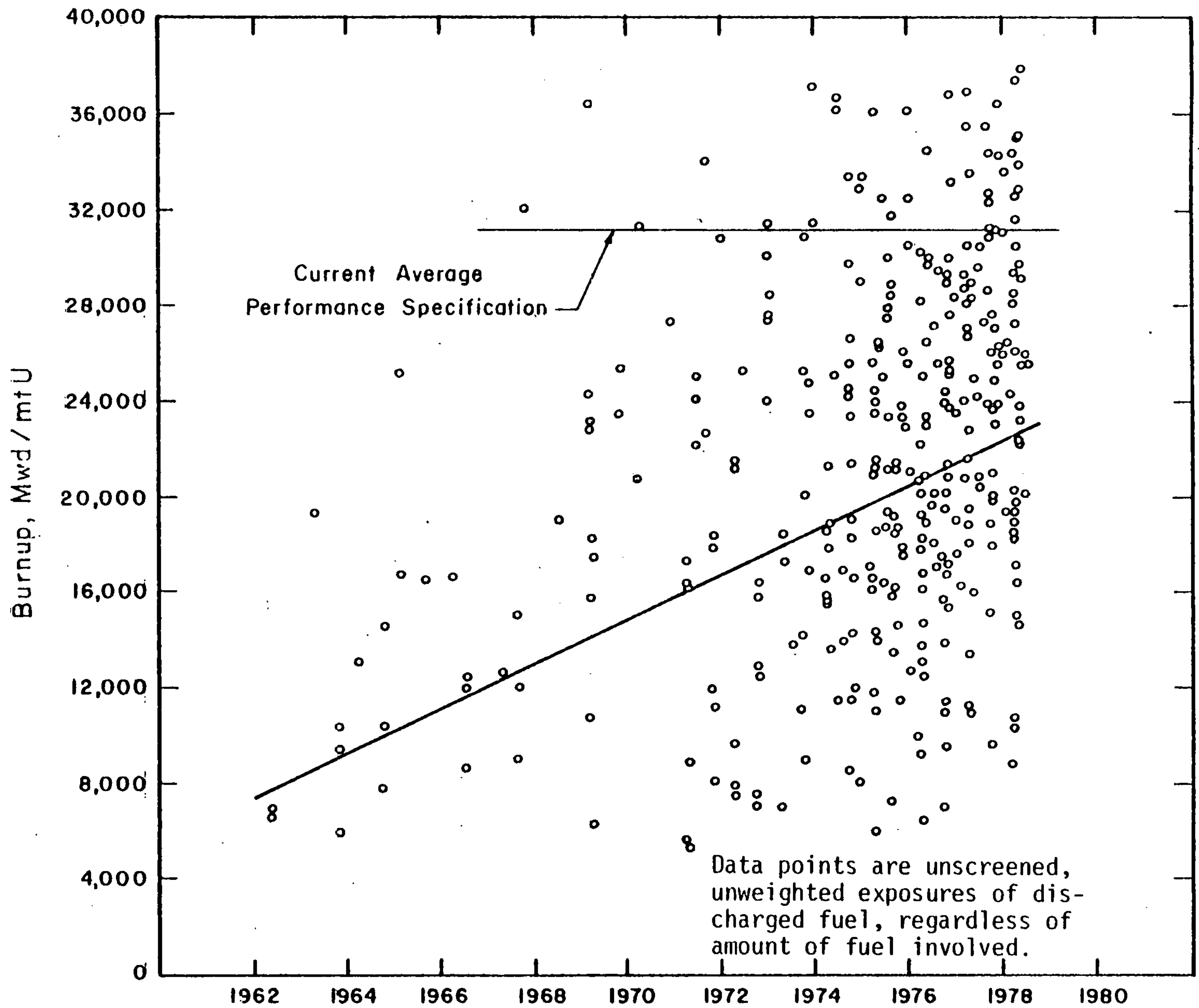

Fig. 2.1 Burnup in fuel discharged from operating nuclear power plants.

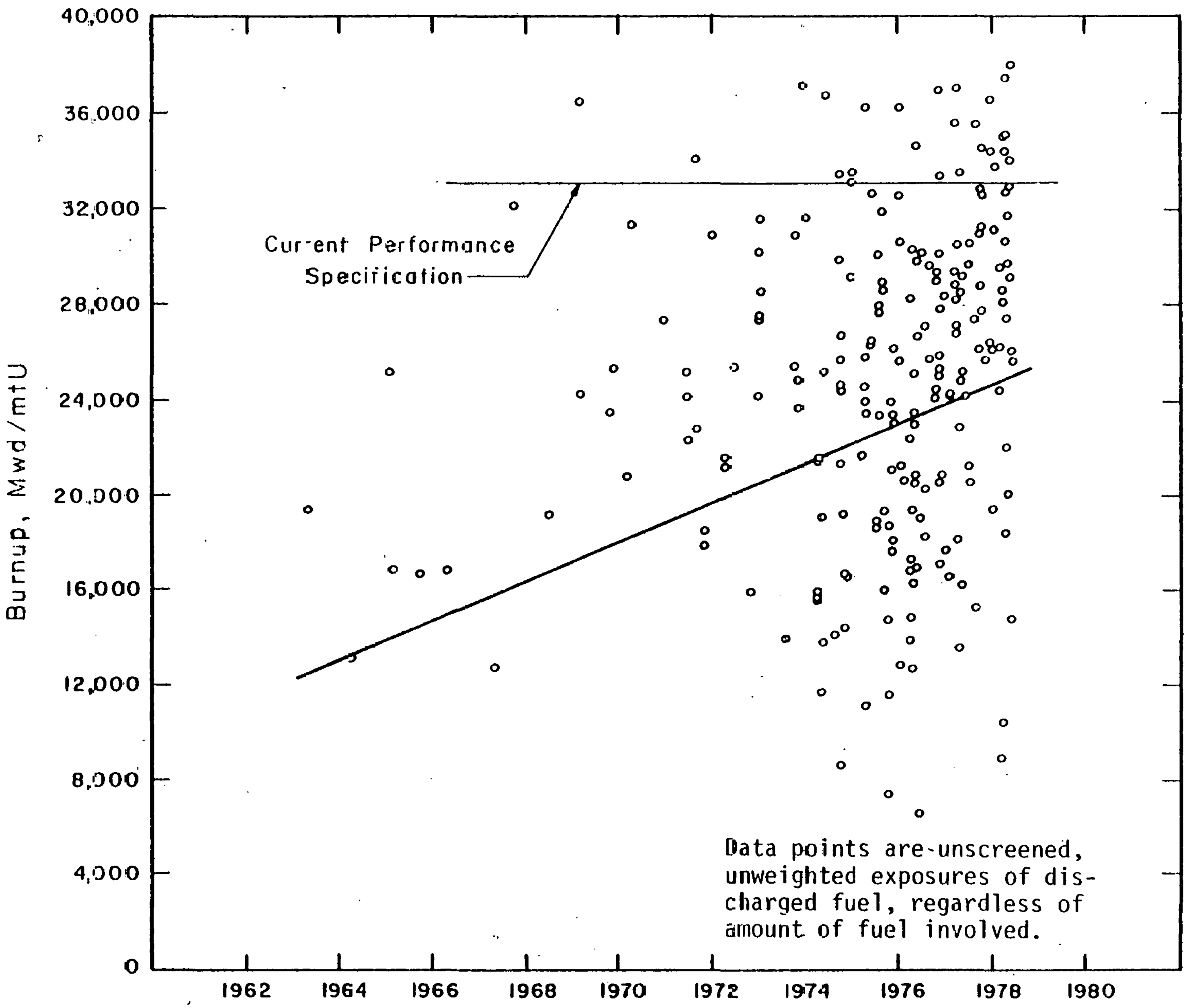

Fig. 2.2 Burnup in fuel discharged from operating pressurized water reactor plants.

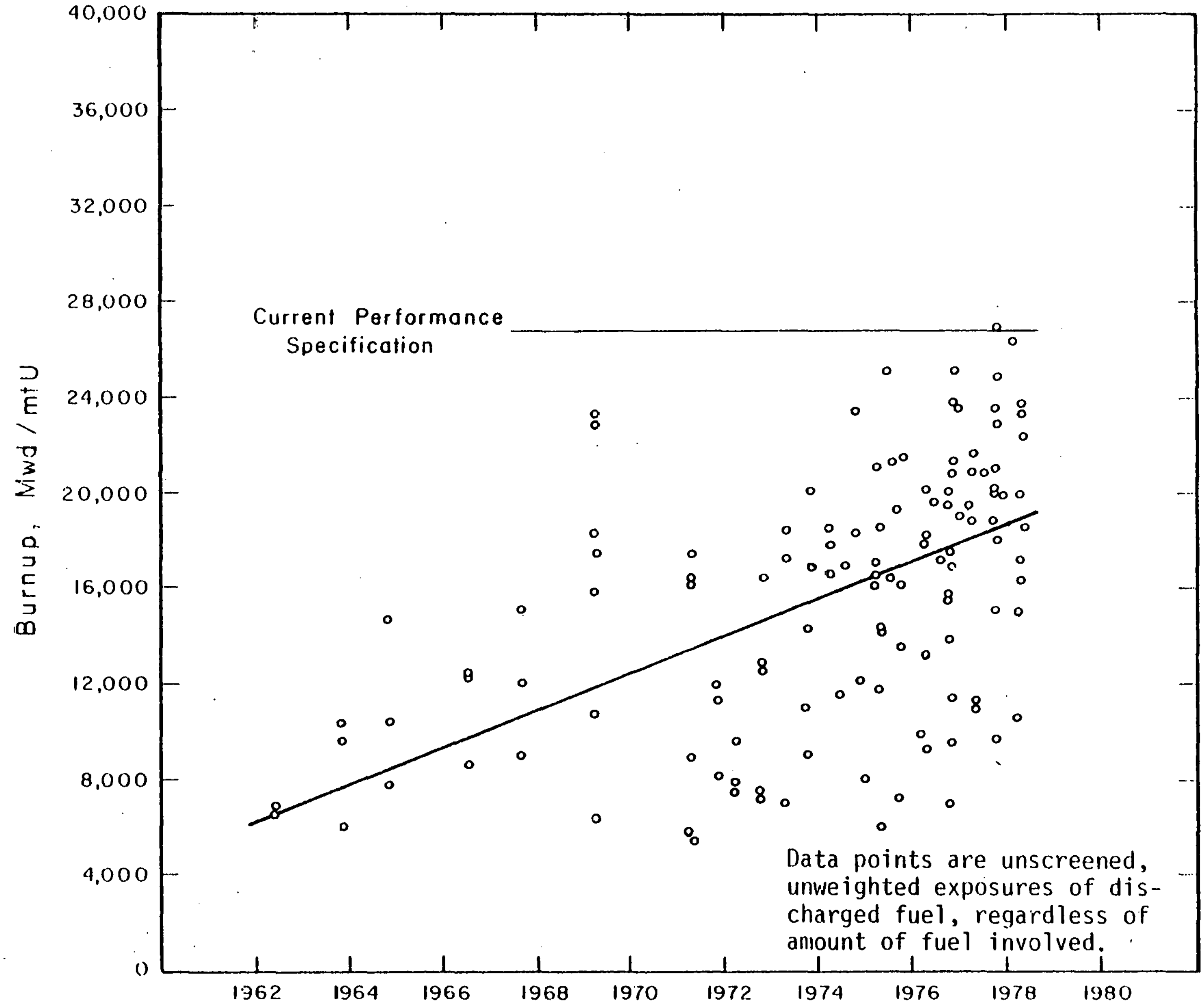

Fig. 2.3 Burnup in fuel discharged from operating boiling water reactor plants.

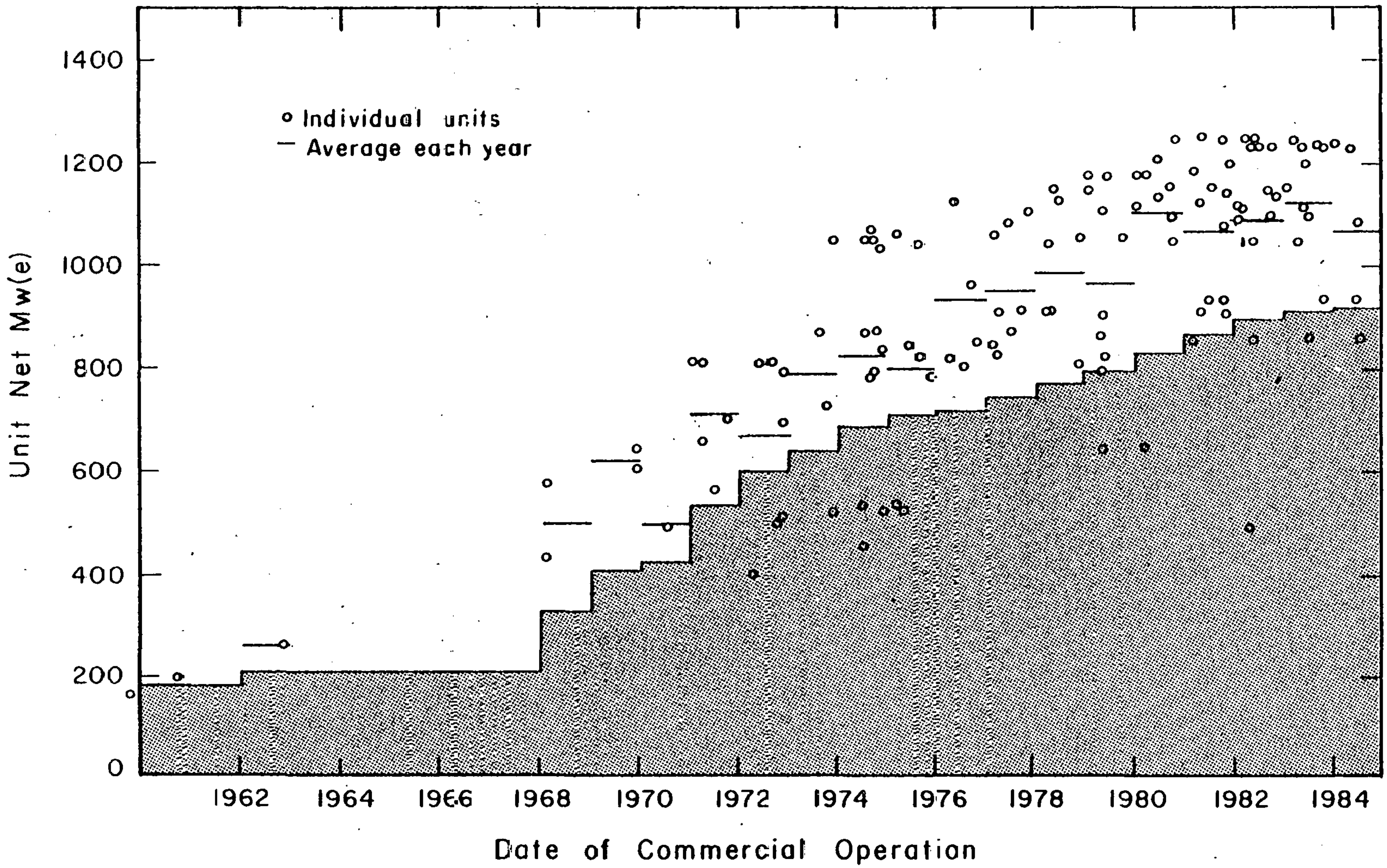

Fig. 2.4 Time dependent trend in nuclear power reactor unit installed capacity.

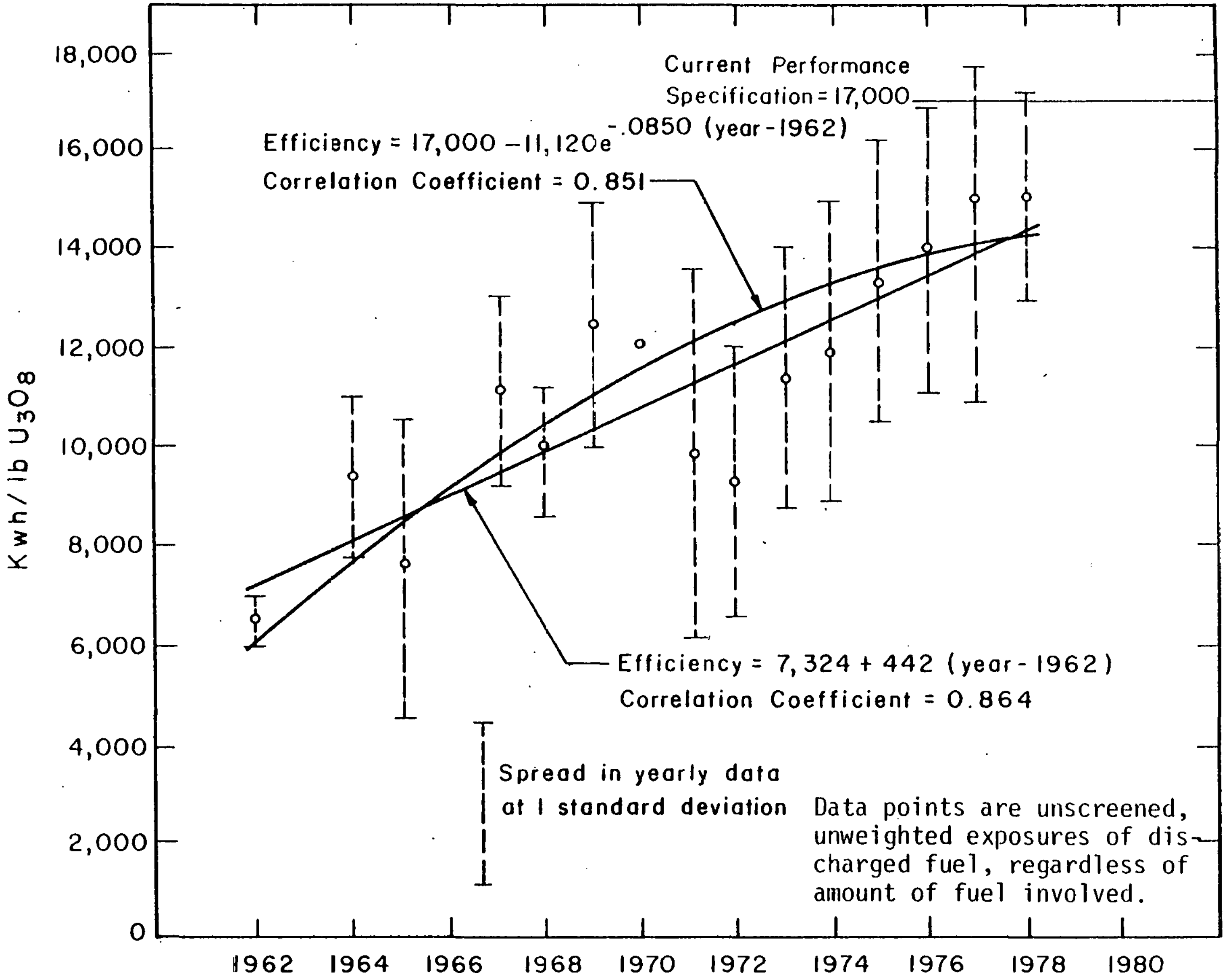

Fig. 2.5 Trend in fuel utilization efficiency (all plants).

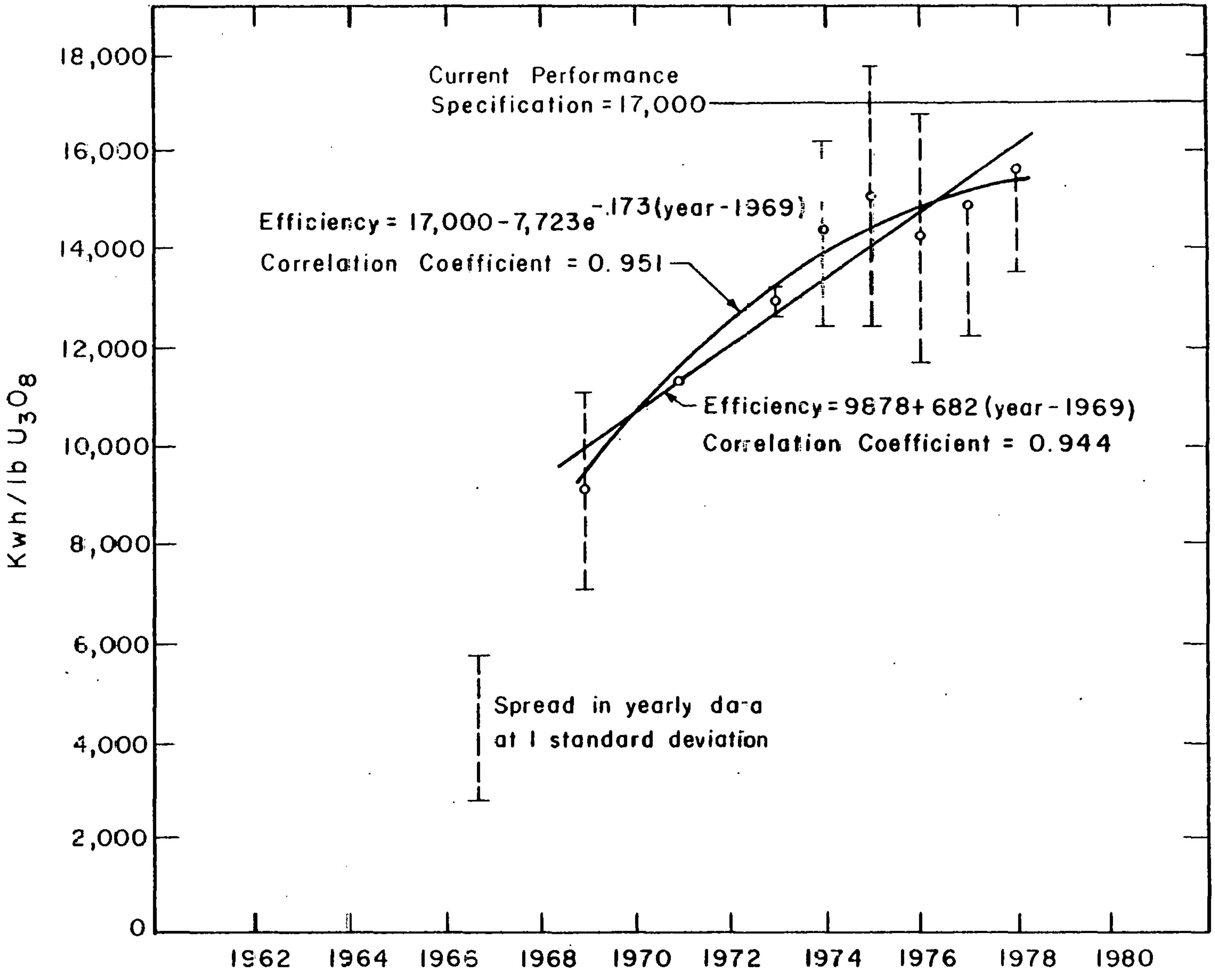

Fig. 2.6 Trend in fuel utilization efficiency (all plants, screened data).

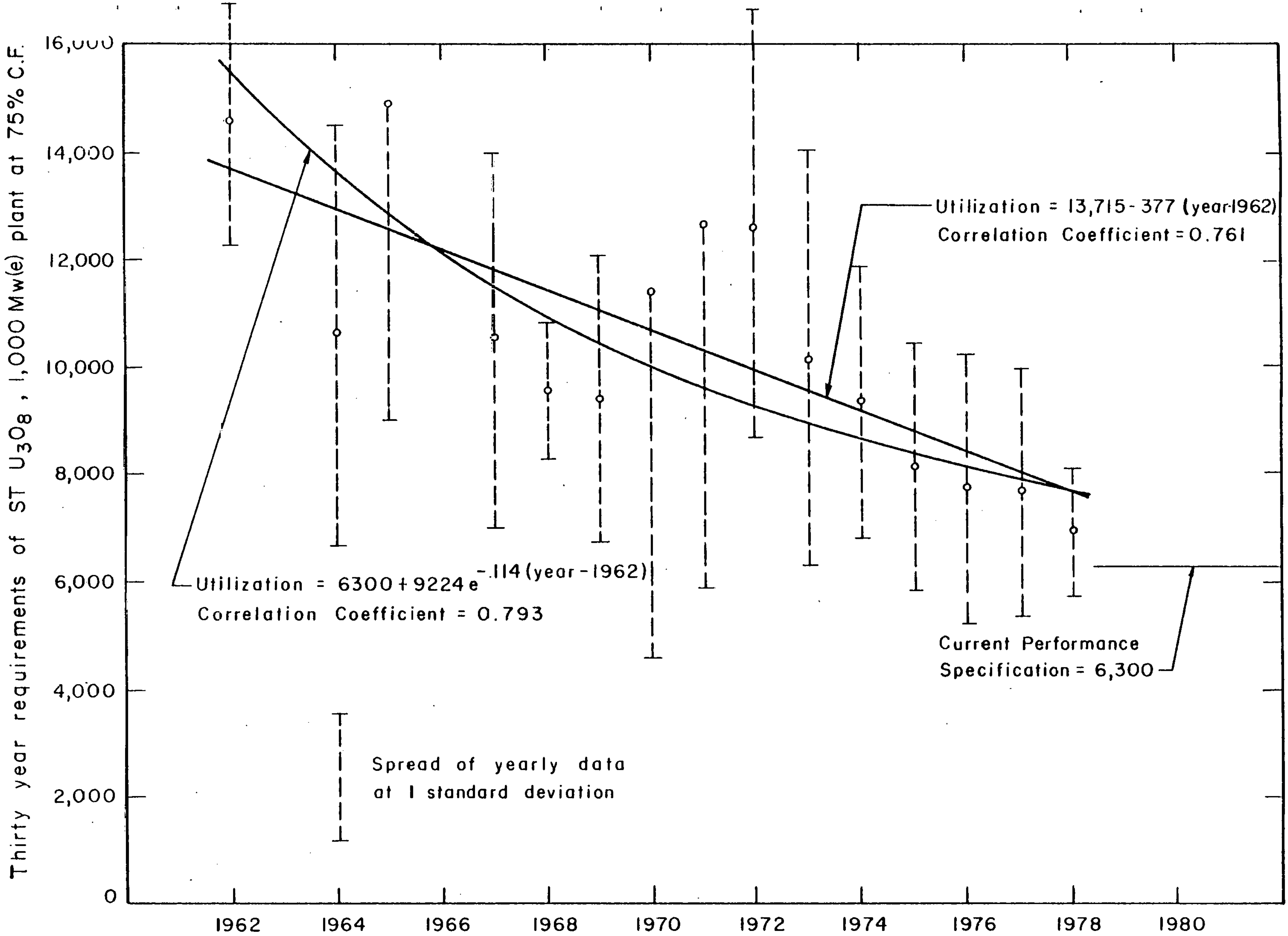

Fig. 2.7 Trend in resource utilization (all plants without SS clad fuel, unscreened data).

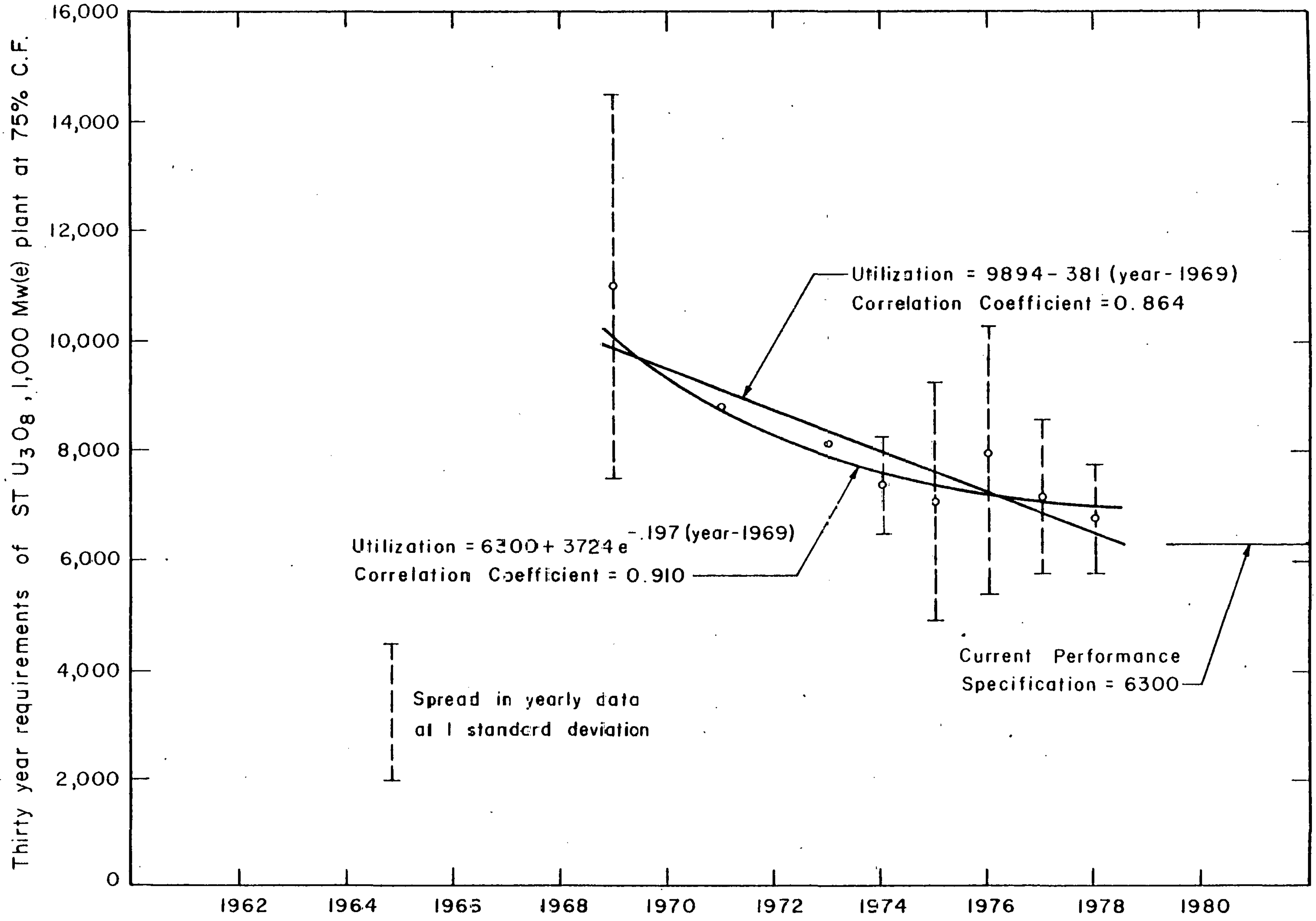

Fig. 2.8 Trend in resource utilization (all plants, screened data).

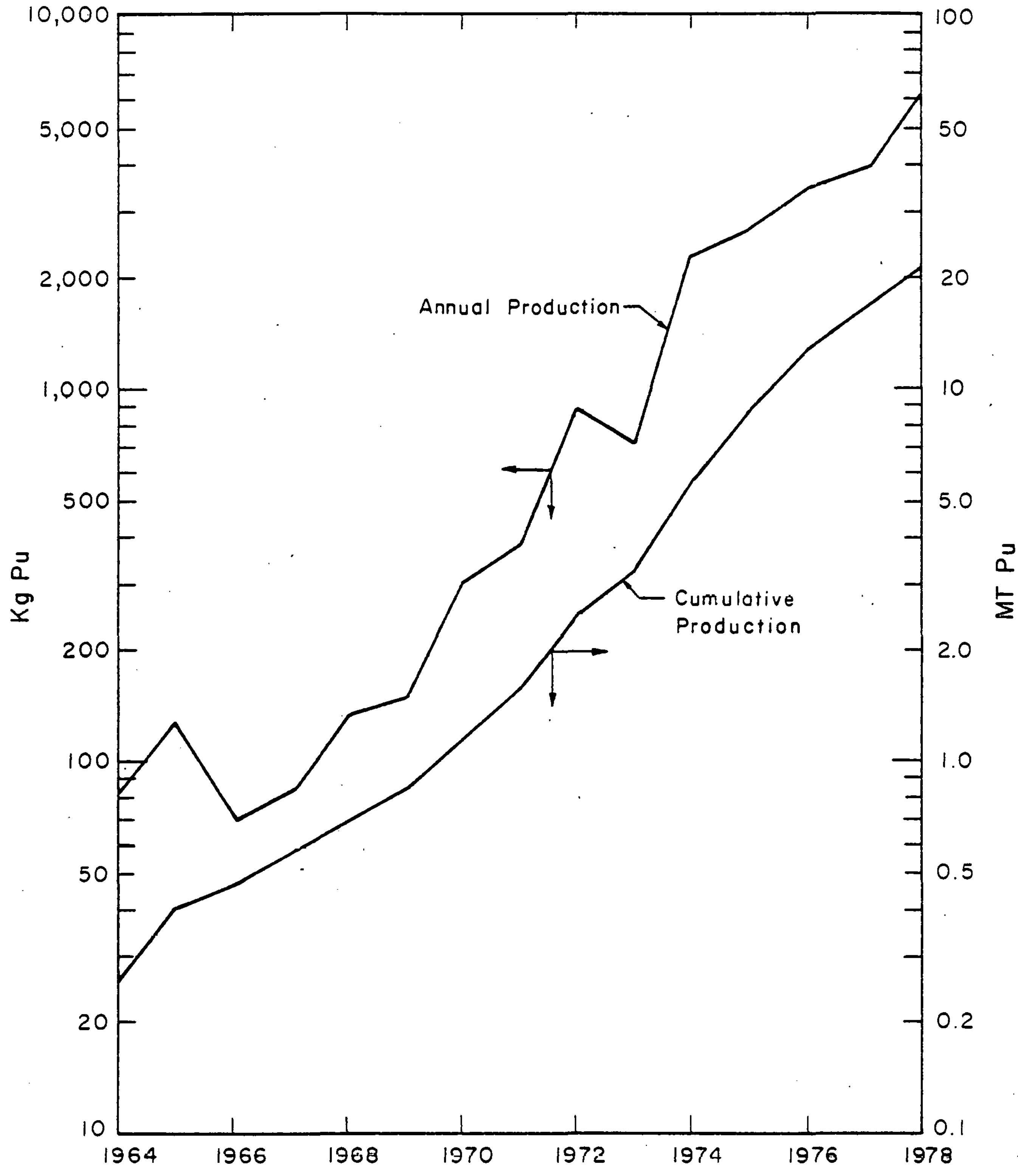

Fig. 2.9 Estimated plutonium production in operating nuclear power plants.

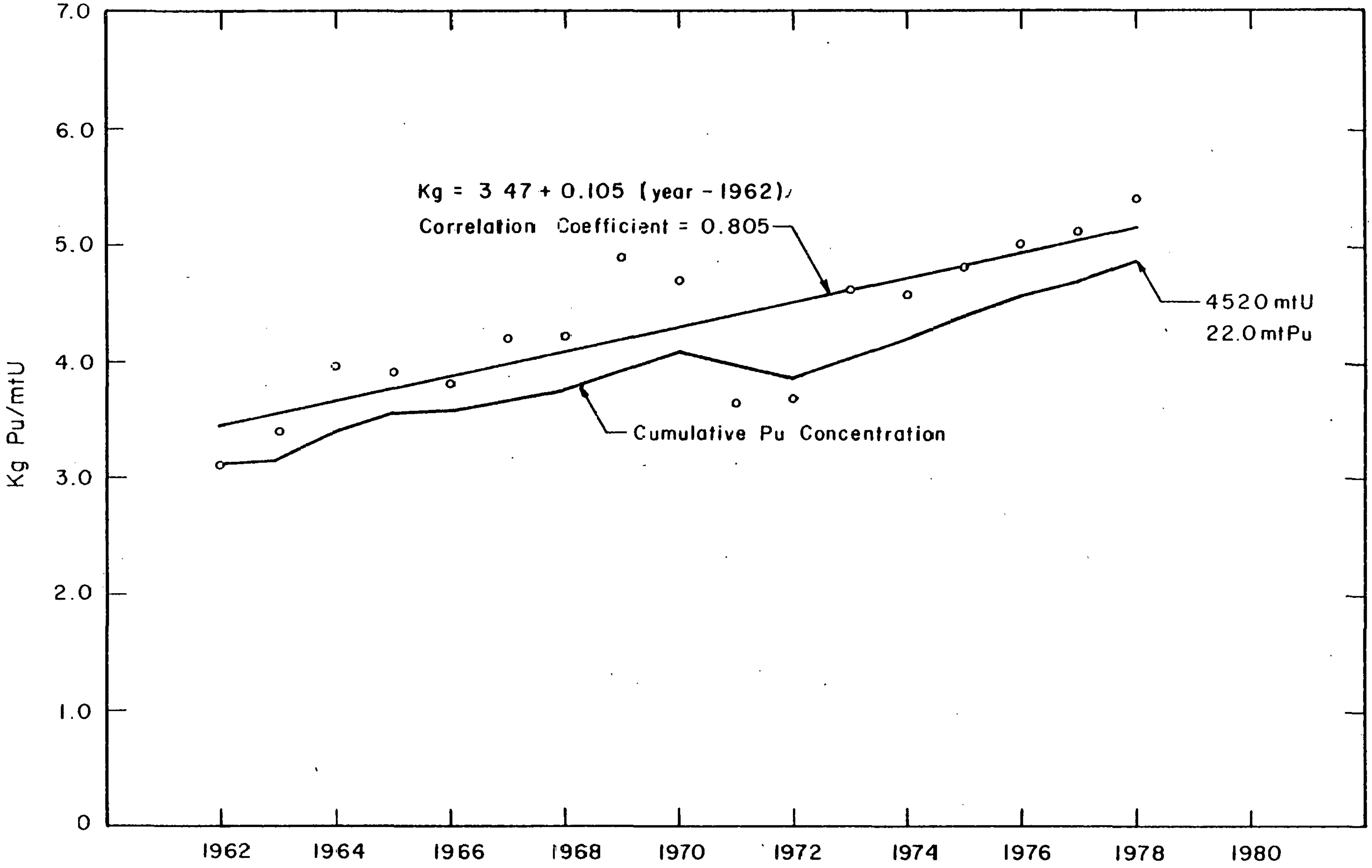

Fig. 2.10 Fissile plutonium content in discharged fuel from operating nuclear power plants.

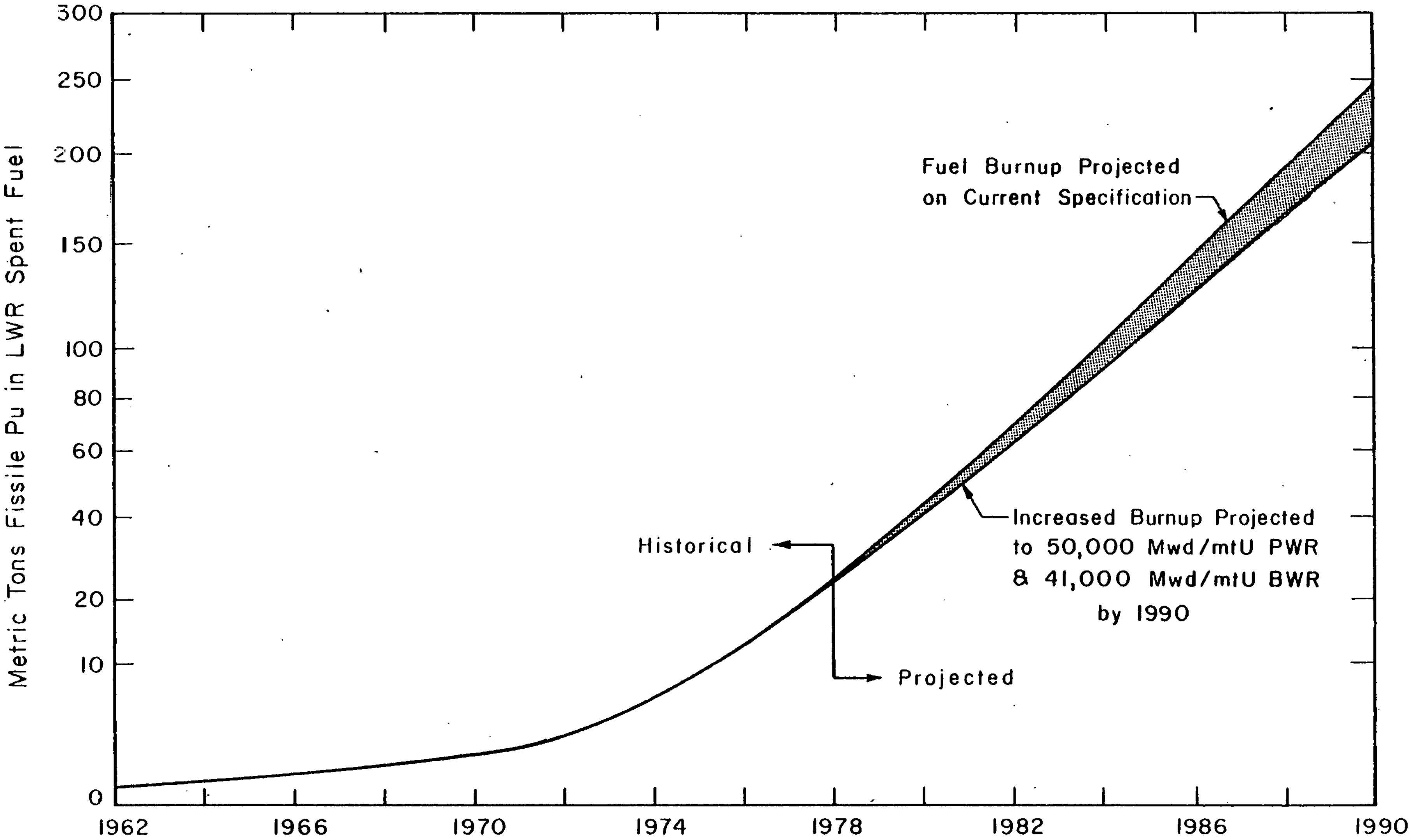

Fig. 2.11 Historical and projected quantities of plutonium produced in nuclear power plants.

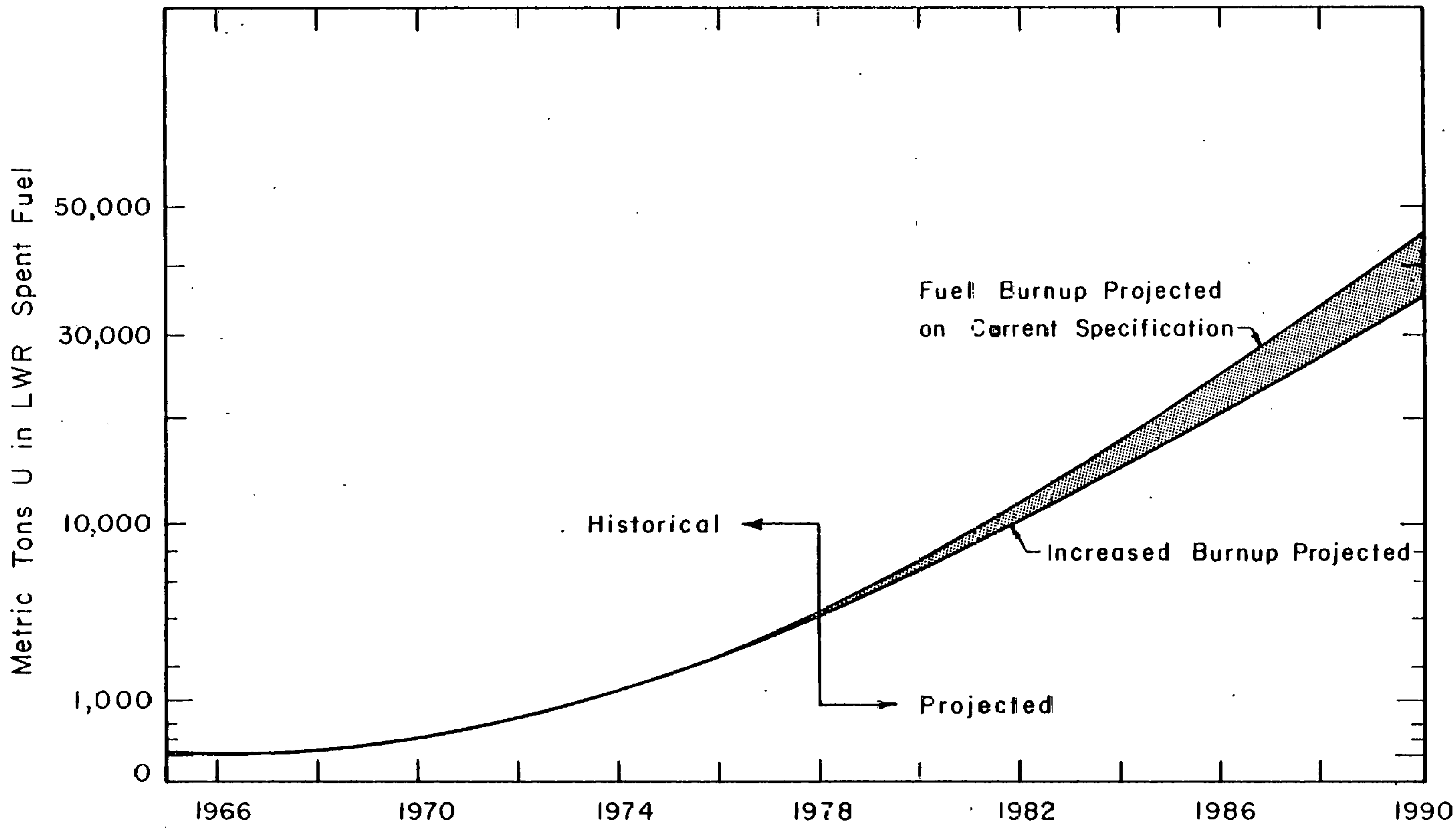

Fig. 2.12 Historical and projected total quantities of Uranium in discharged fuel.

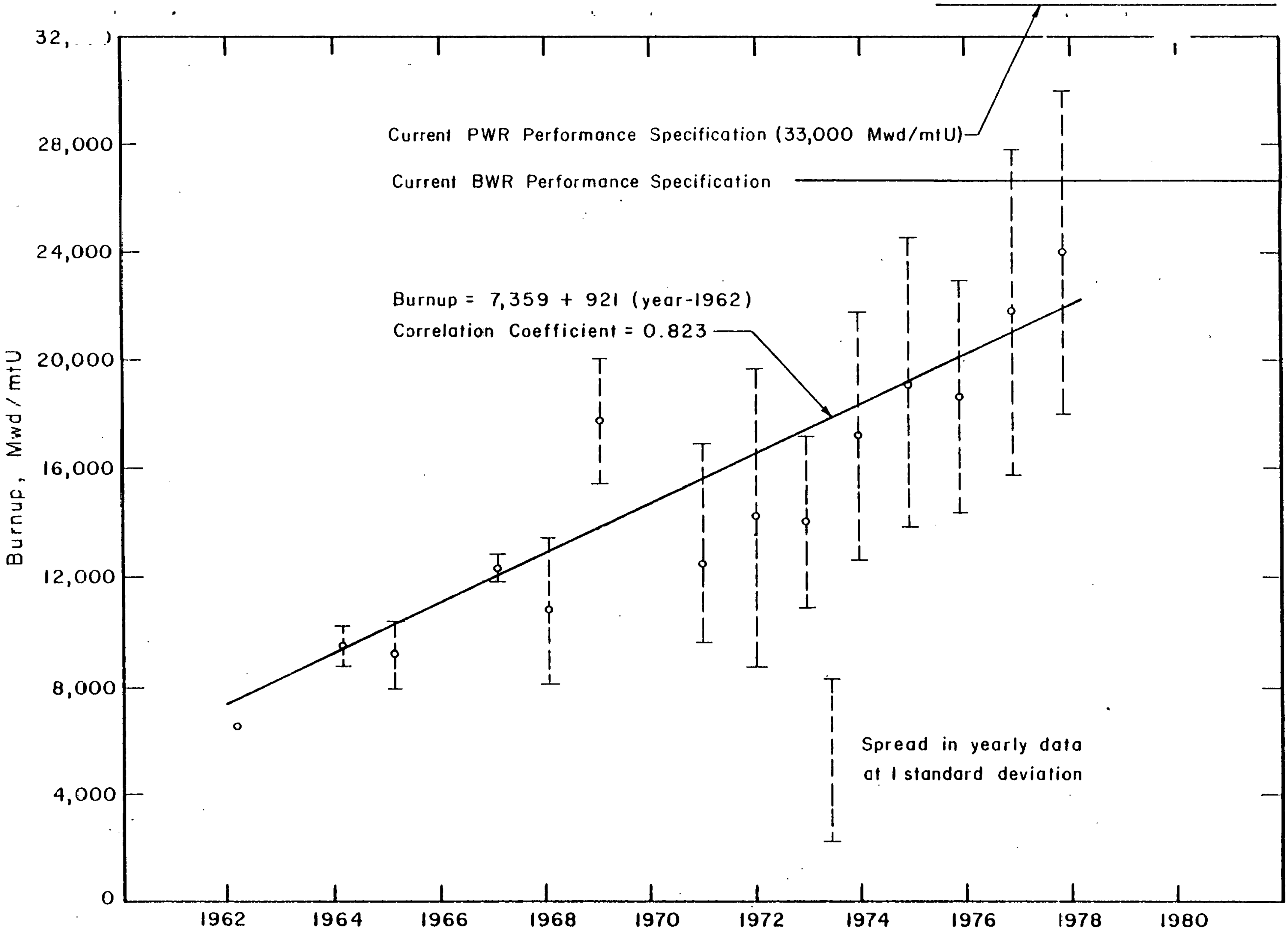

Fig. 5.1 Trend in fuel burnup experience (all plants, unscreened data).

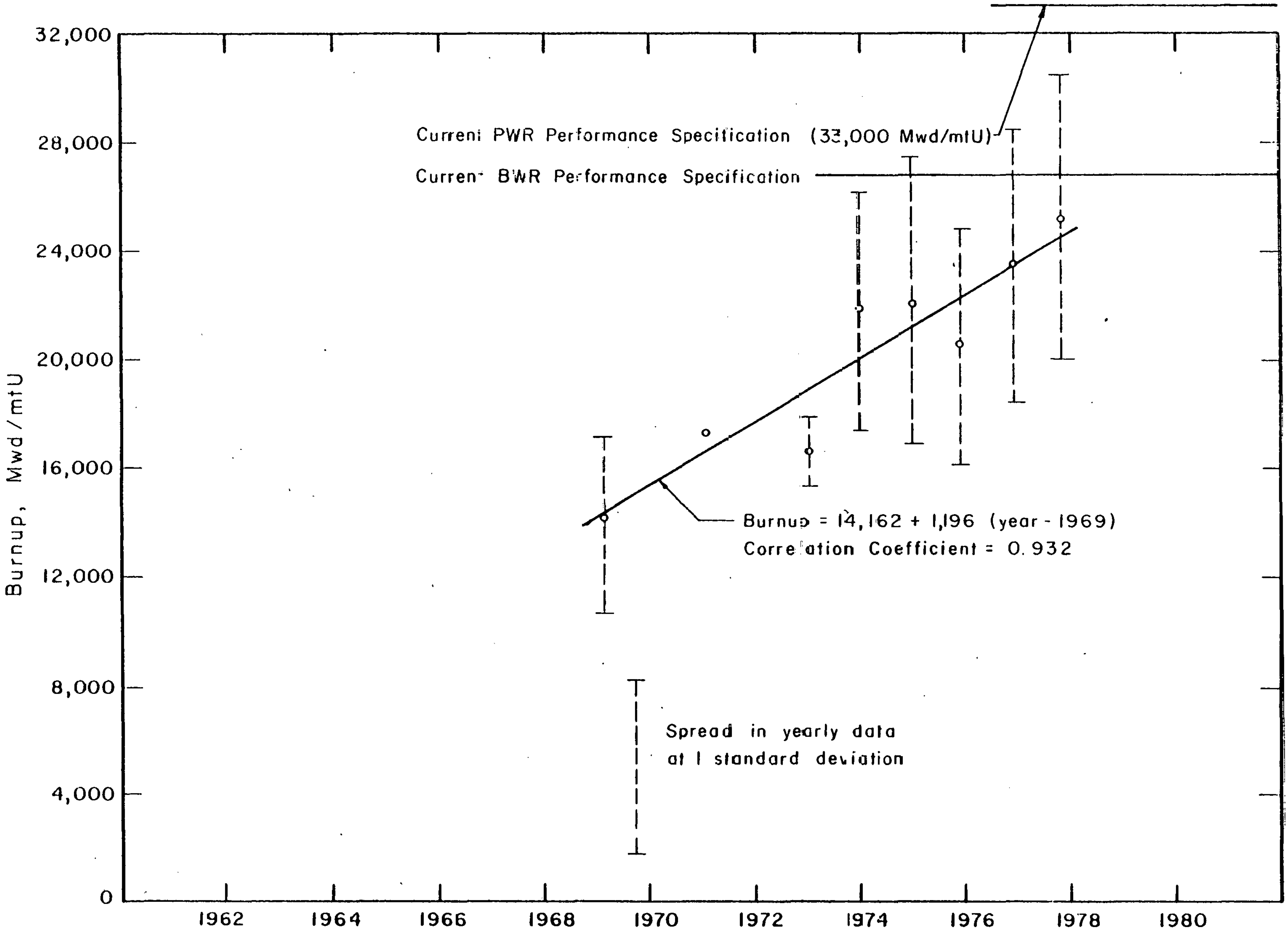

Fig. 5.2 Trend in fuel burnup experience (all plants, screened data).

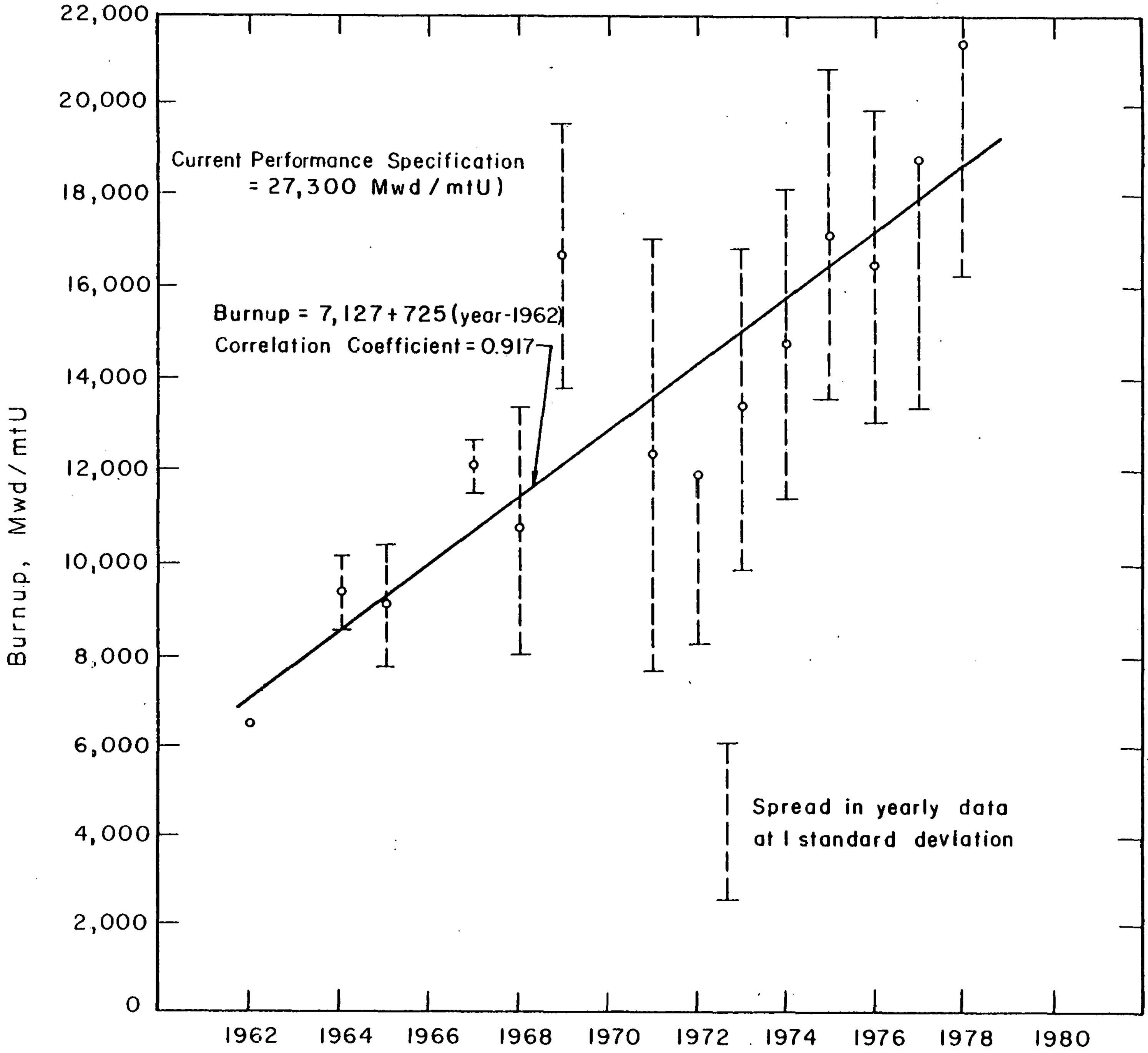

Fig. 5.3 Trend in fuel burnup experience in boiling water reactors (unscreened data).

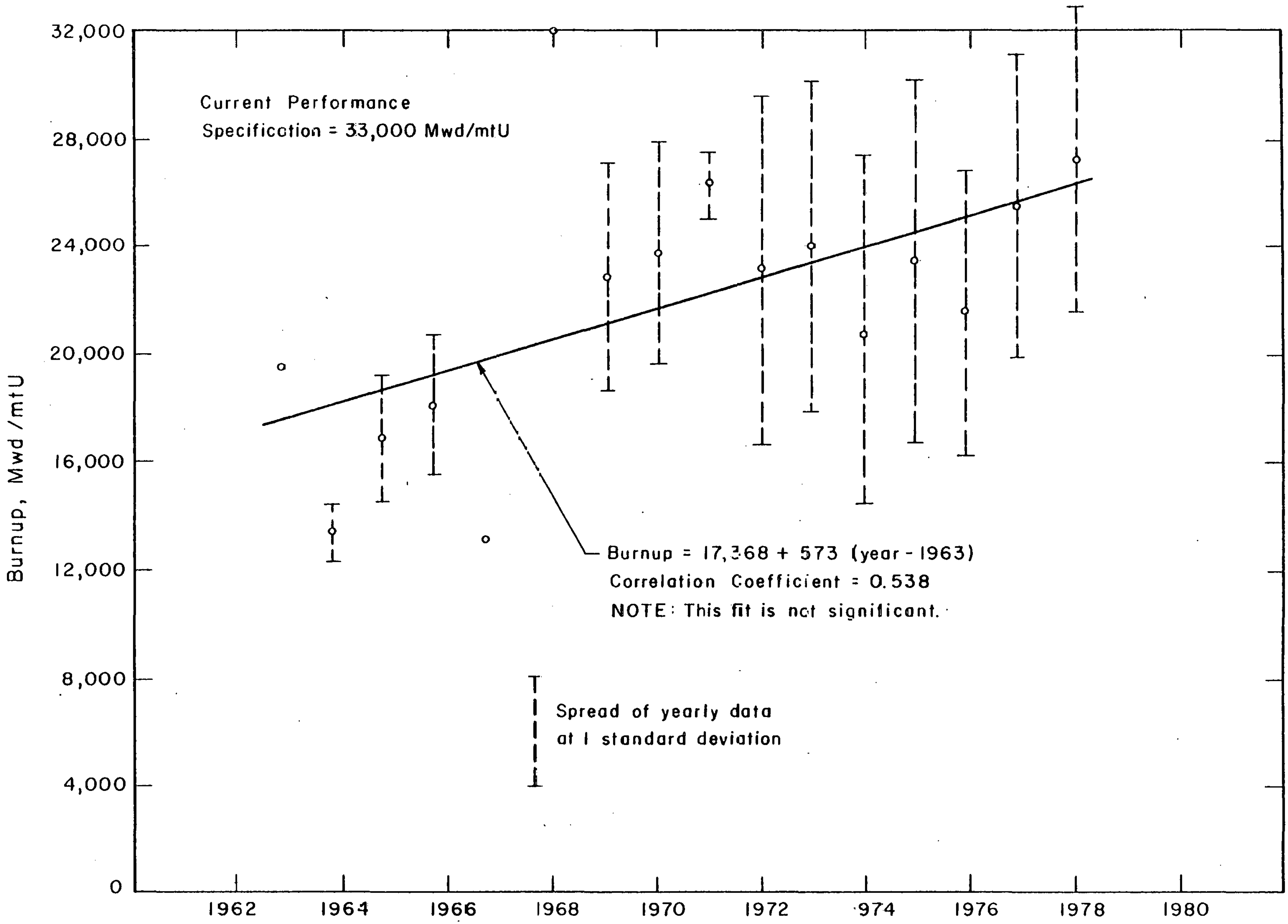

Fig. 5.4 Trend in fuel burnup experience in pressurized water reactors (unscreened data).

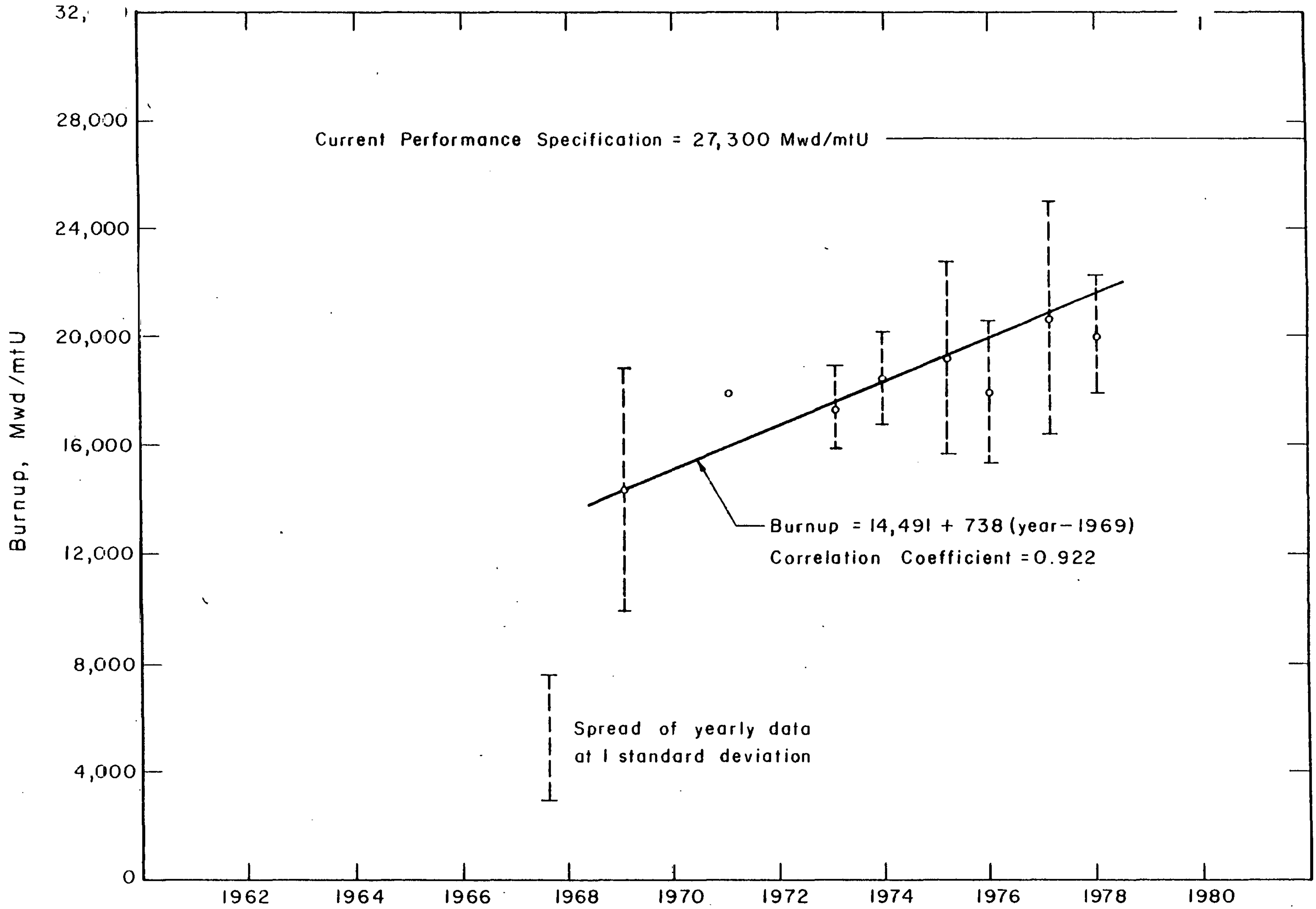

Fig. 5.5 Trend in fuel burnup experience in boiling water reactors (screened data).

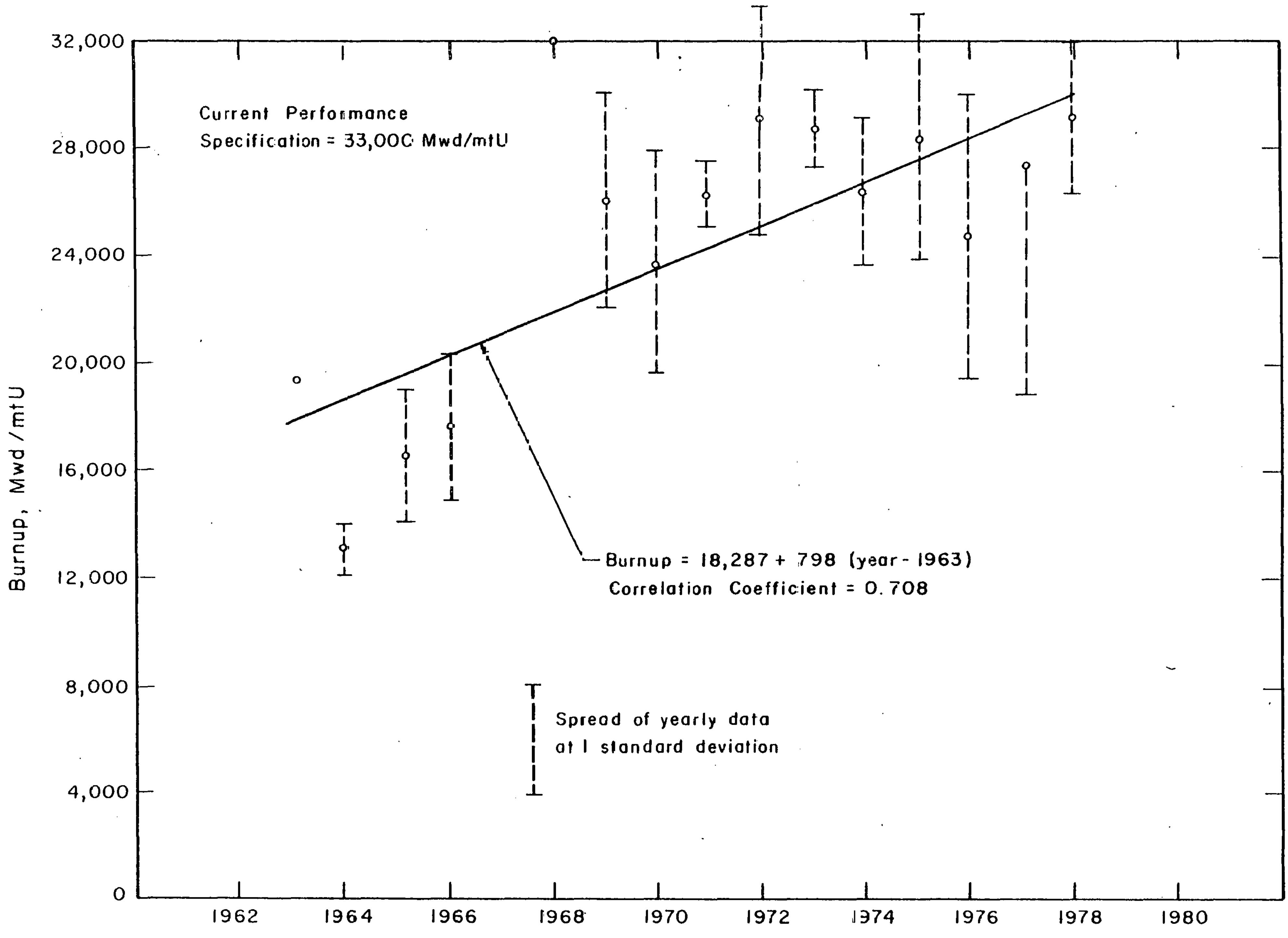

Fig. 5.6 Trend in fuel burnup experience in pressurized water reactors (with SS clad fuel, screened data).

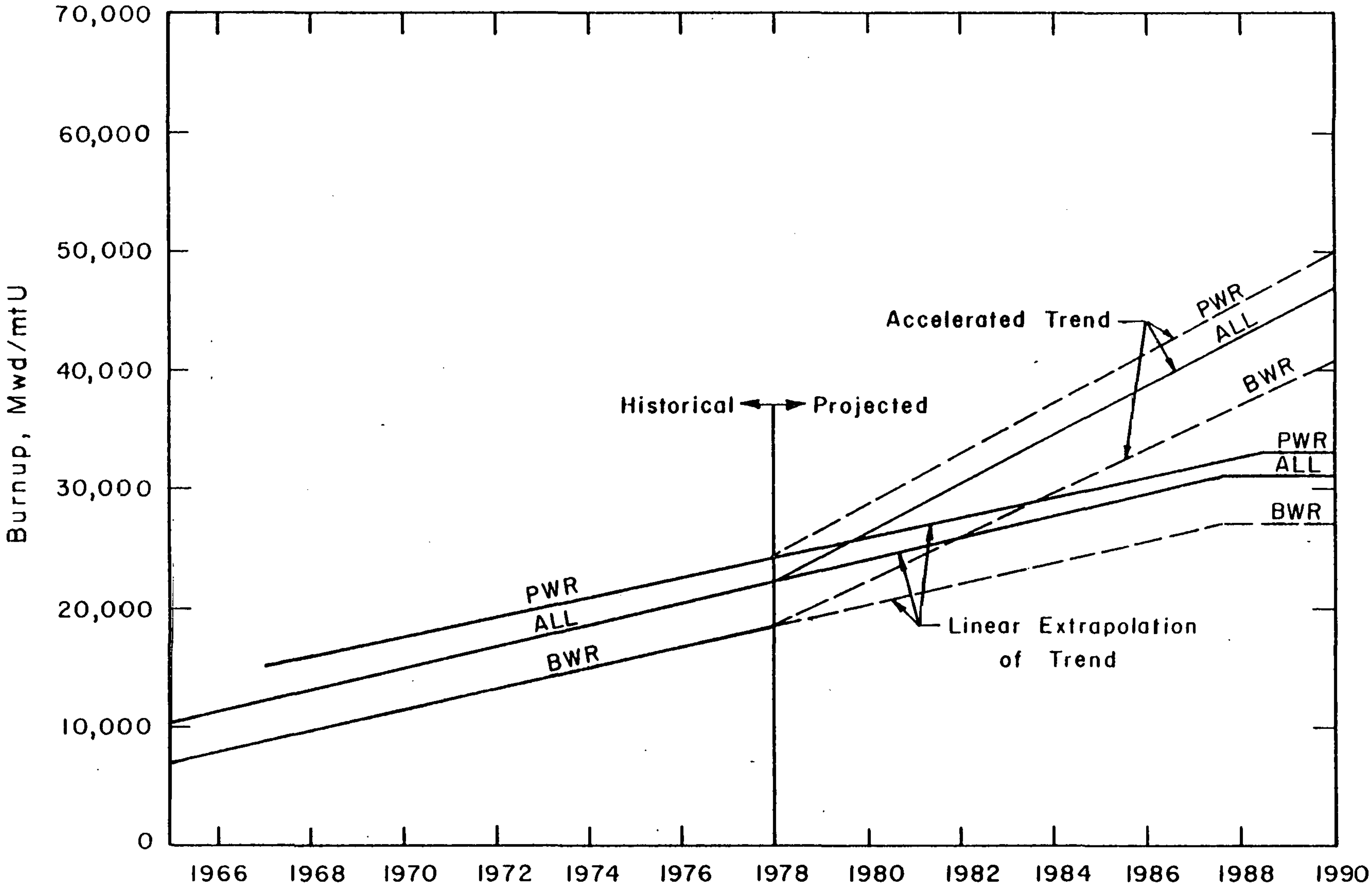

Fig. 5.7 Historical and projected trends in fuel burnup.

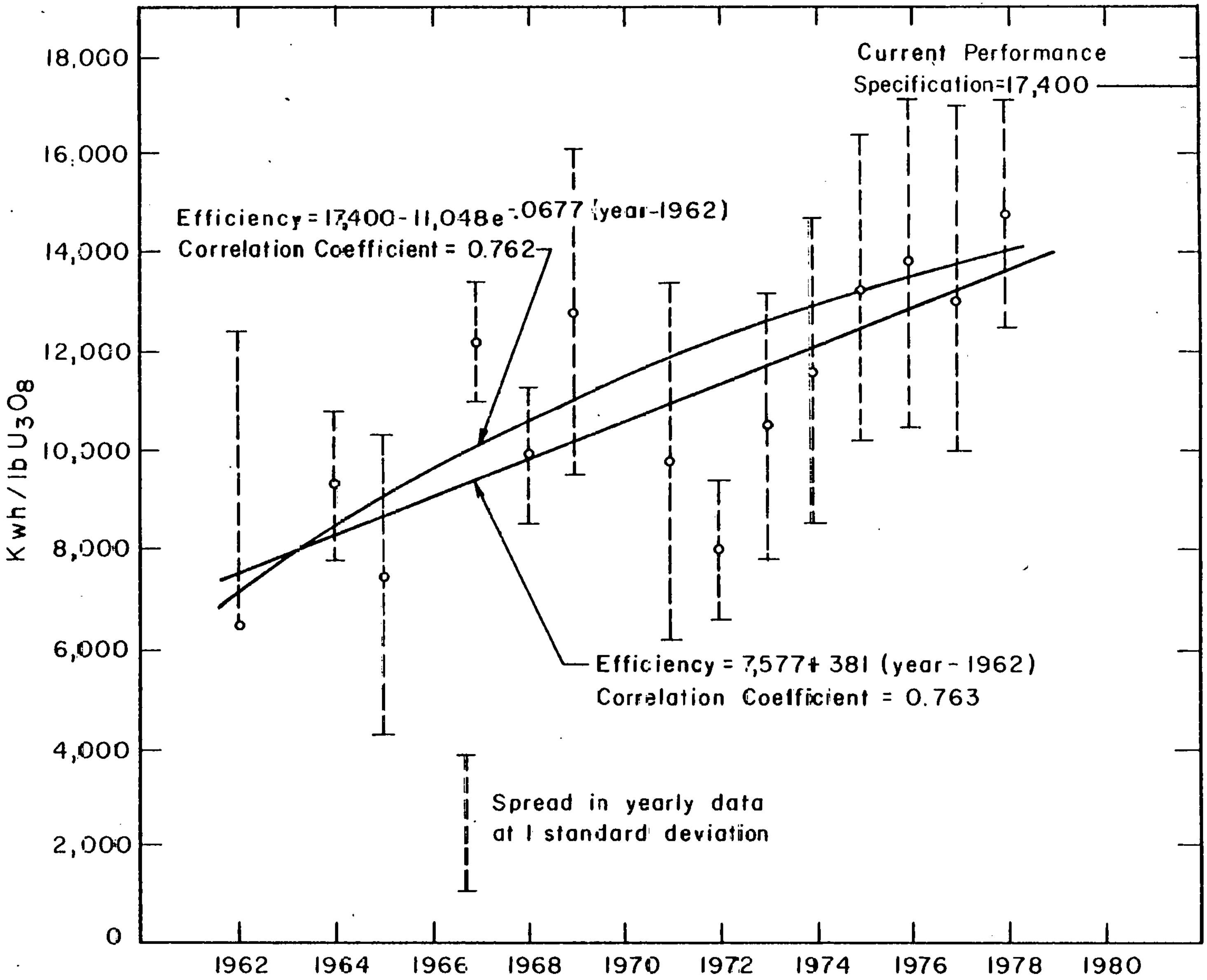

Fig. 5.8 Trend in fuel utilization efficiency in boiling water reactors (unscreened data).

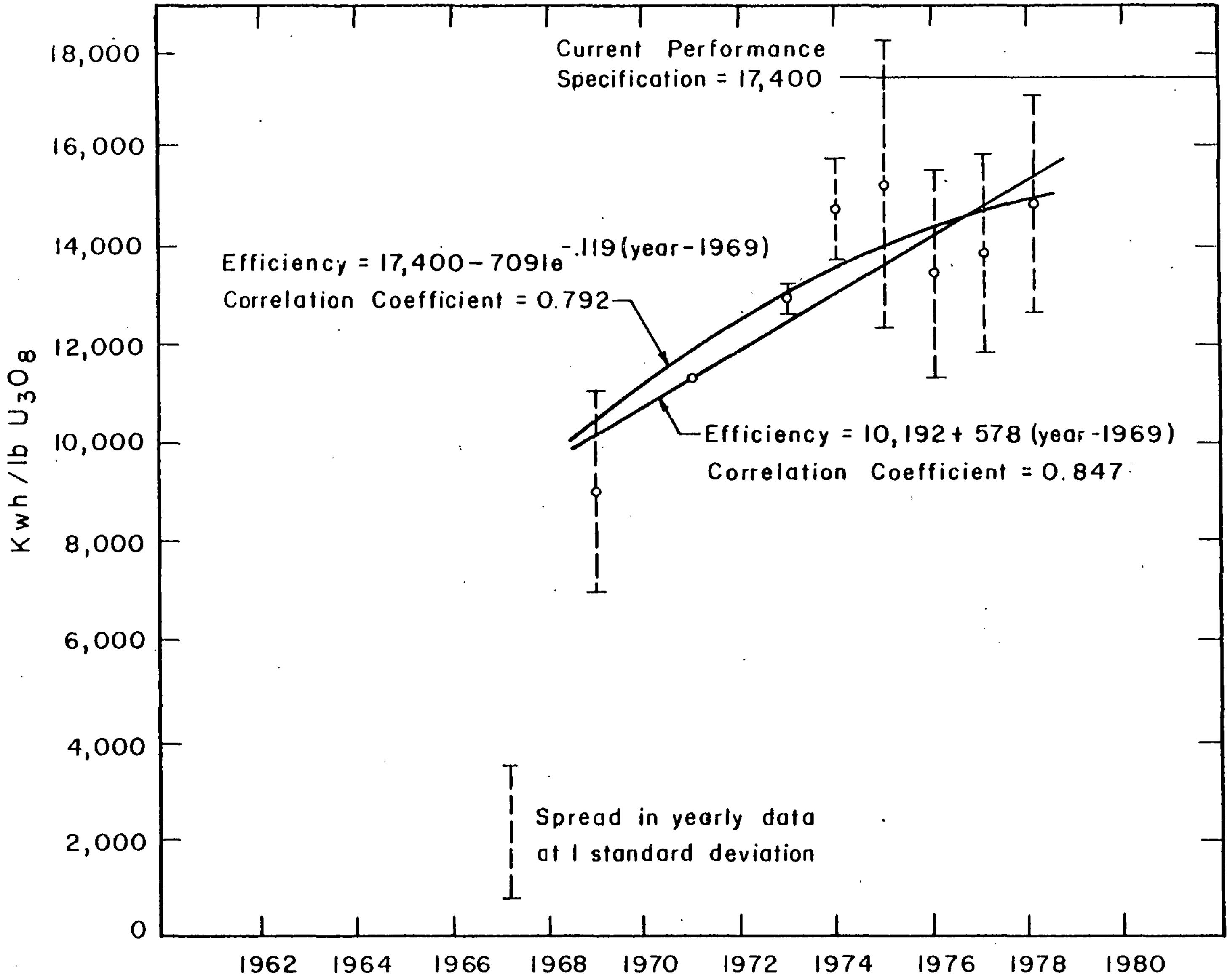

Fig. 5.9 Trend in fuel utilization efficiency in boiling water reactors (screened data).

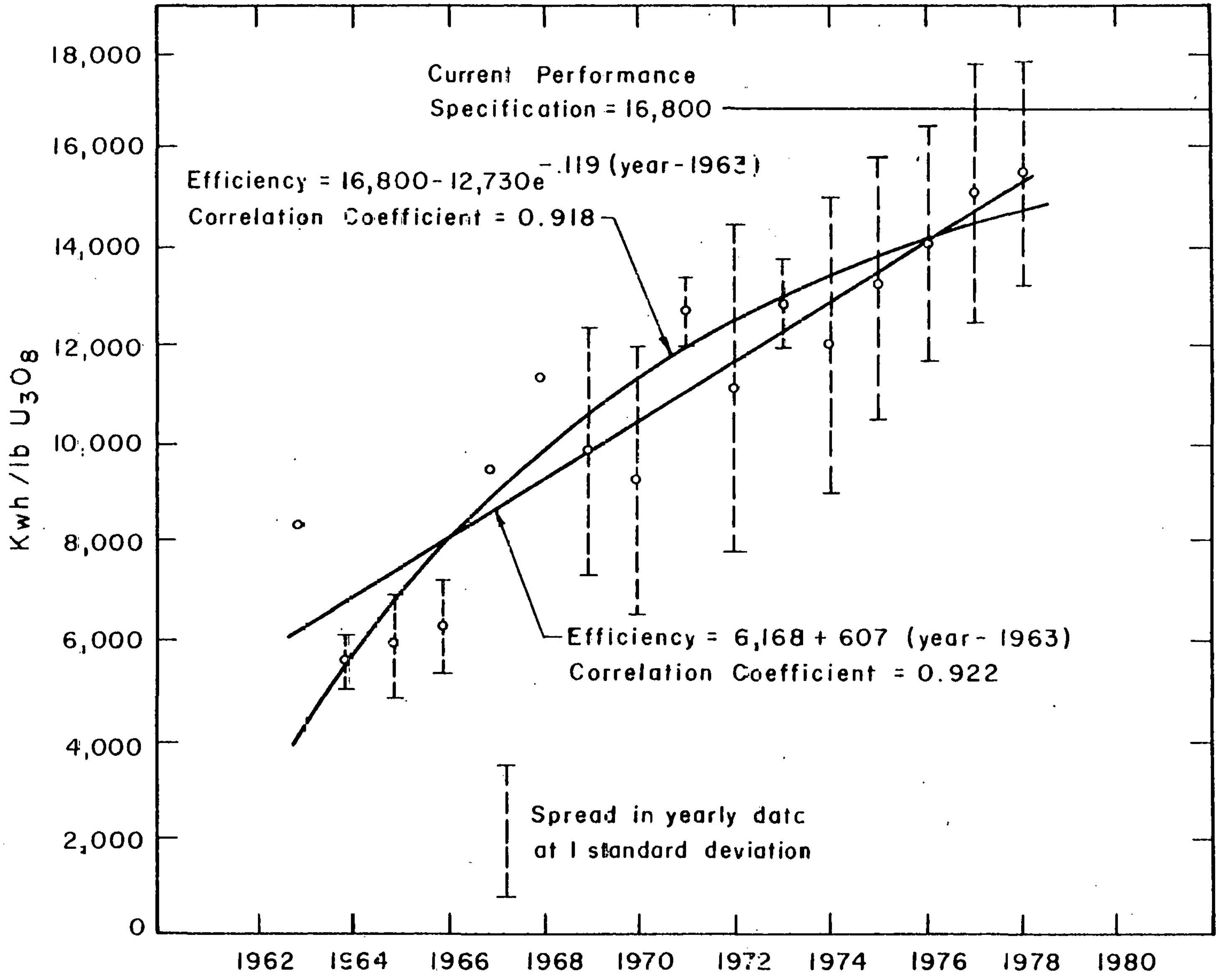

Fig. 5.10 Trend in fuel utilization efficiency in pressurized water reactors (with SS clad fuel, unscreened data).

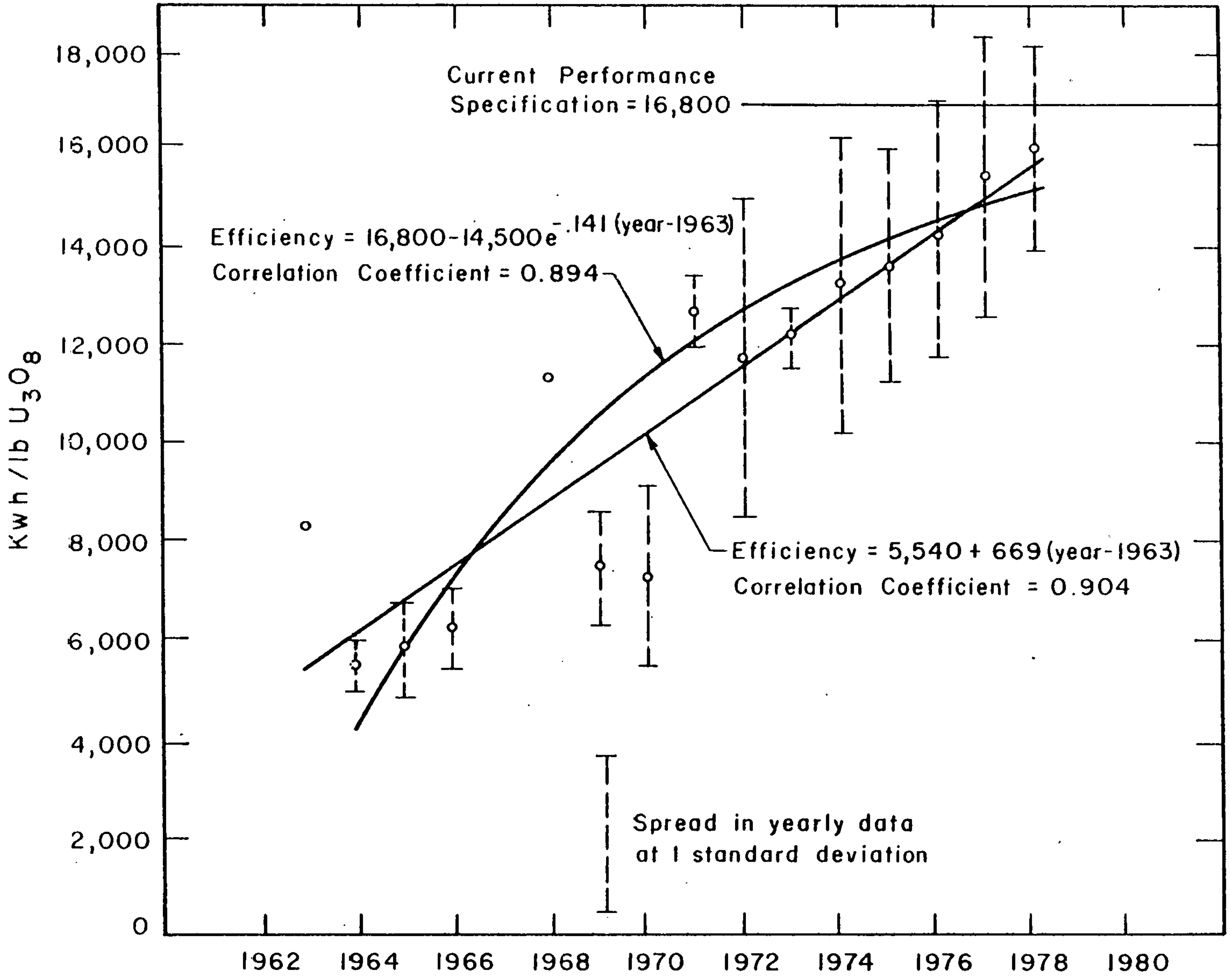

Fig. 5.11 Trend in fuel utilization efficiency in pressurized water reactors (with SS clad fuel, screened data).

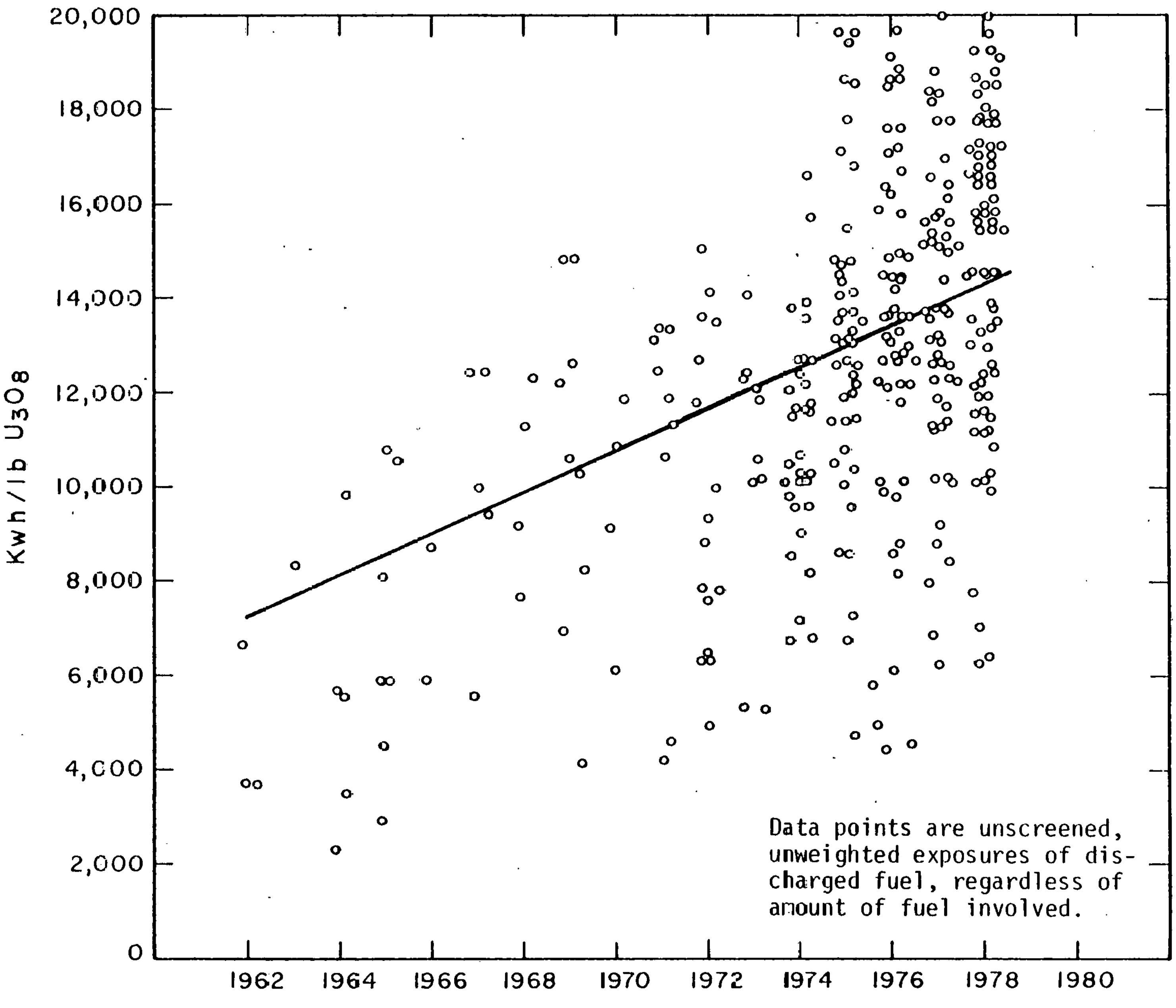

Fig. 5.12 Fuel utilization efficiency data from all plants.

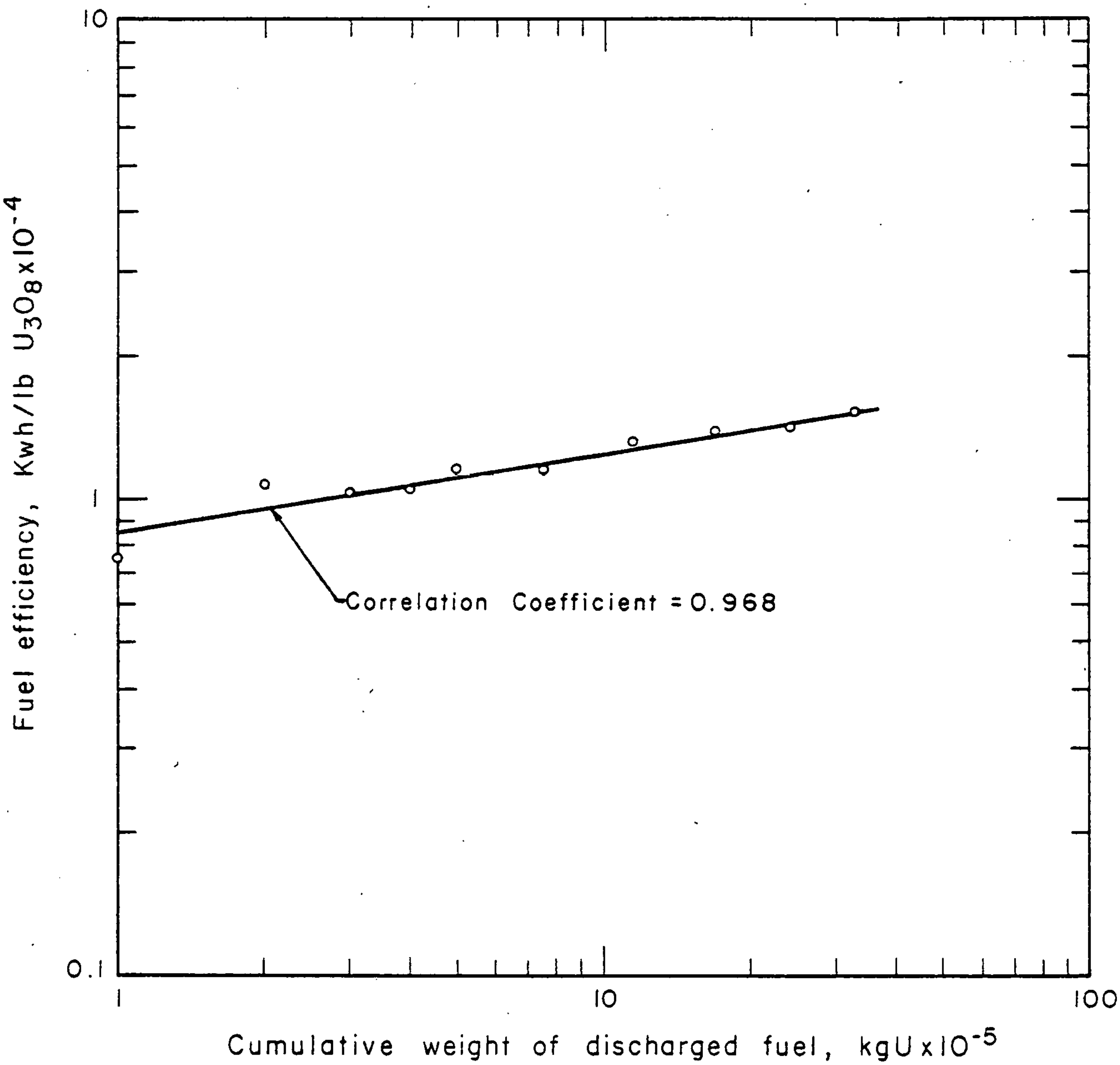

Fig. 5.13 Learning curve correlation for fuel efficiency (kwhr/lb U_3O_8) with total weight of discharged fuel (with SS clad fuel, unscreened data).

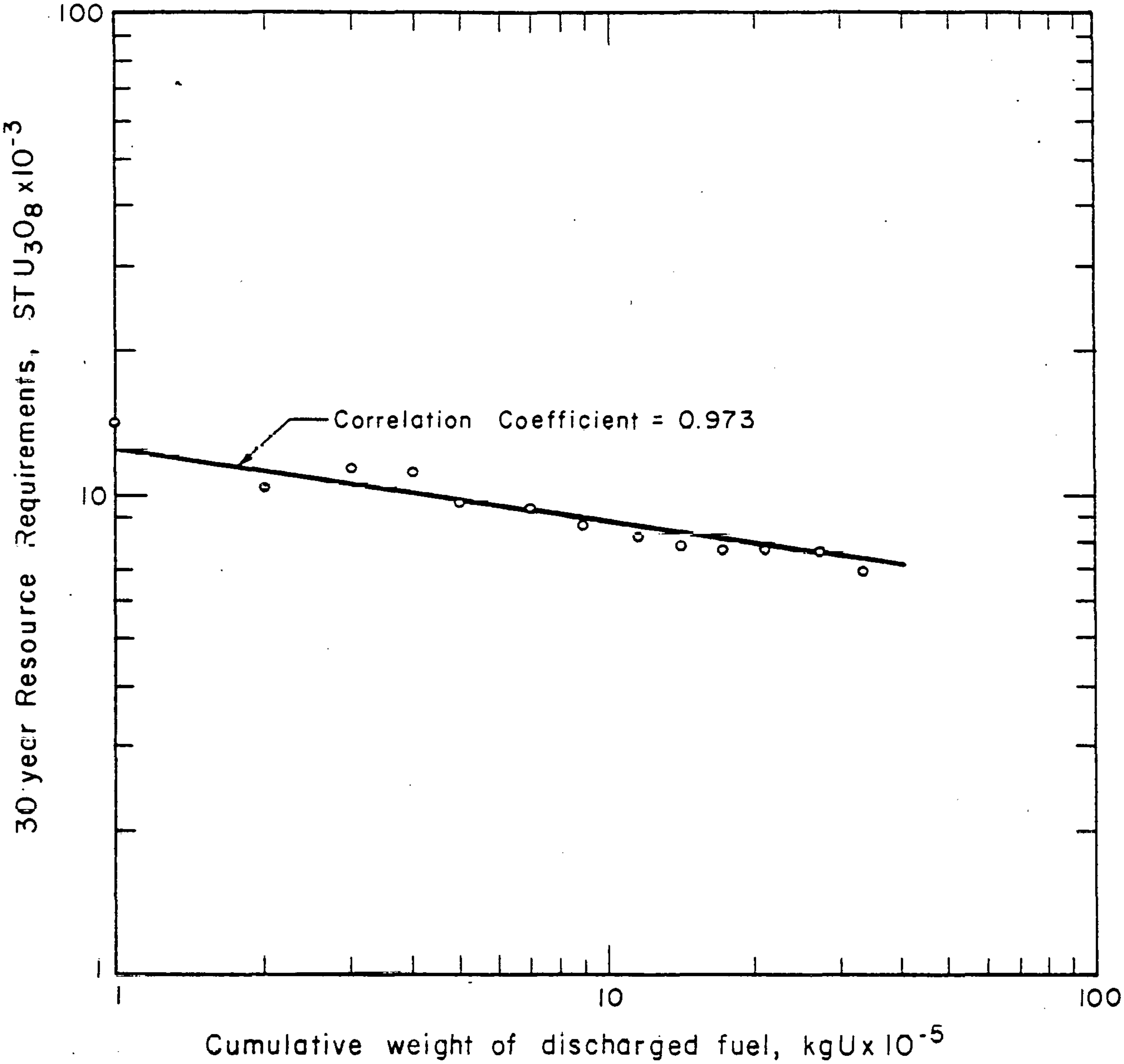

Fig. 5.14 Learning curve correlation for 30-year resource utilization with total weight of discharged fuel (with SS clad fuel, unscreened data).

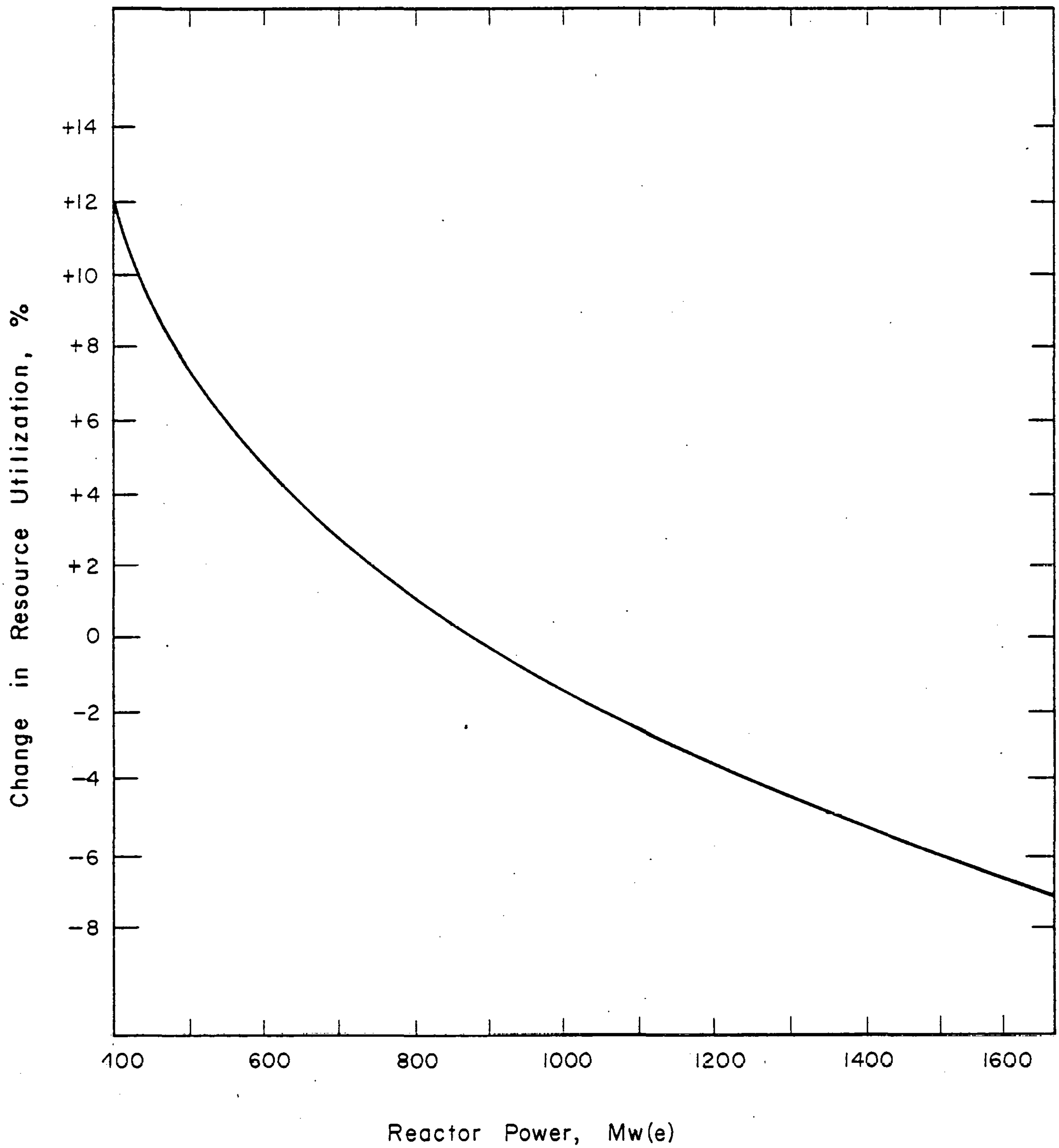

Fig. 6.1 Effect of reactor size on resource utilization.

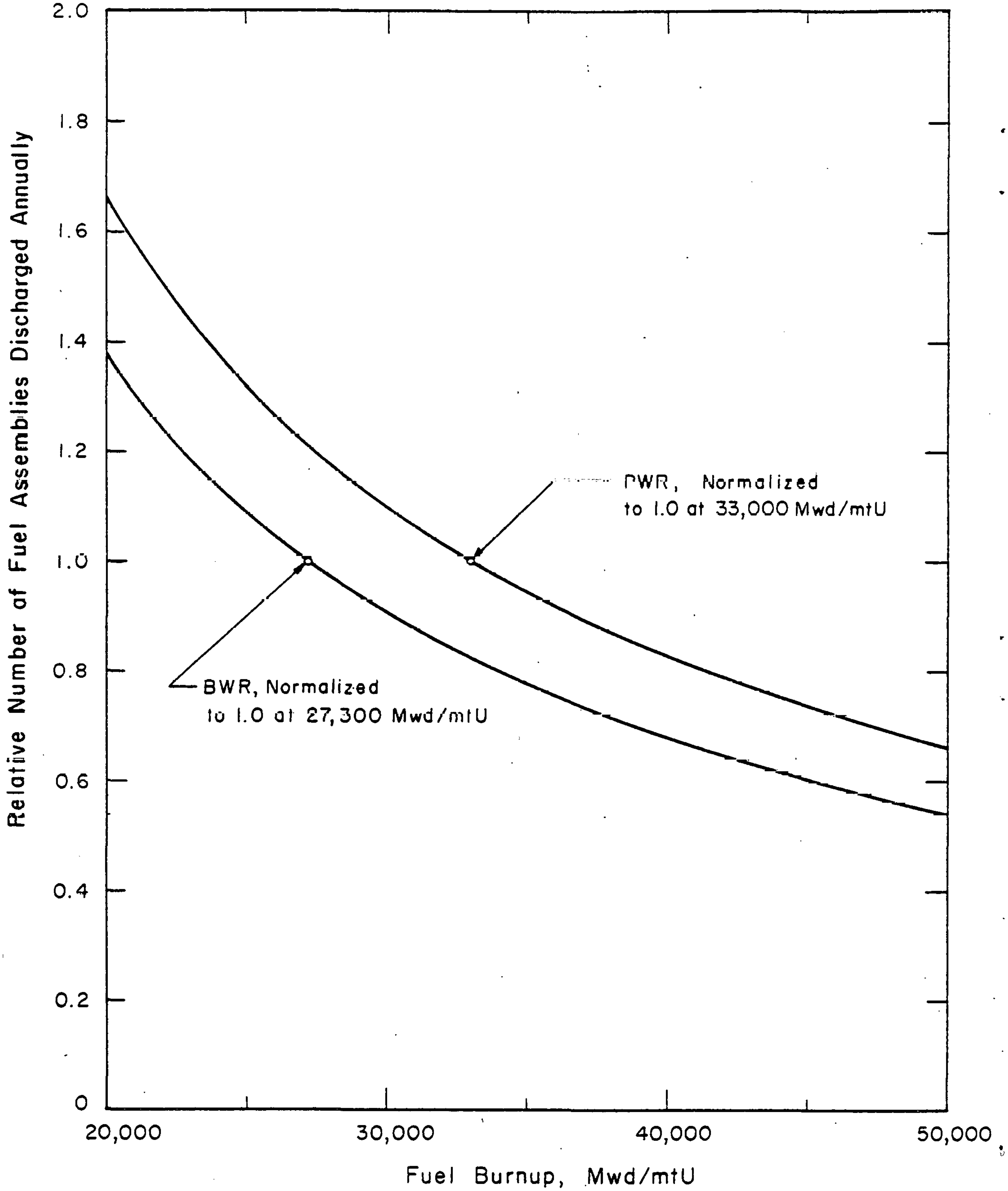

Fig. 6.2 Effect of fuel burnup on relative spent fuel storage requirements.

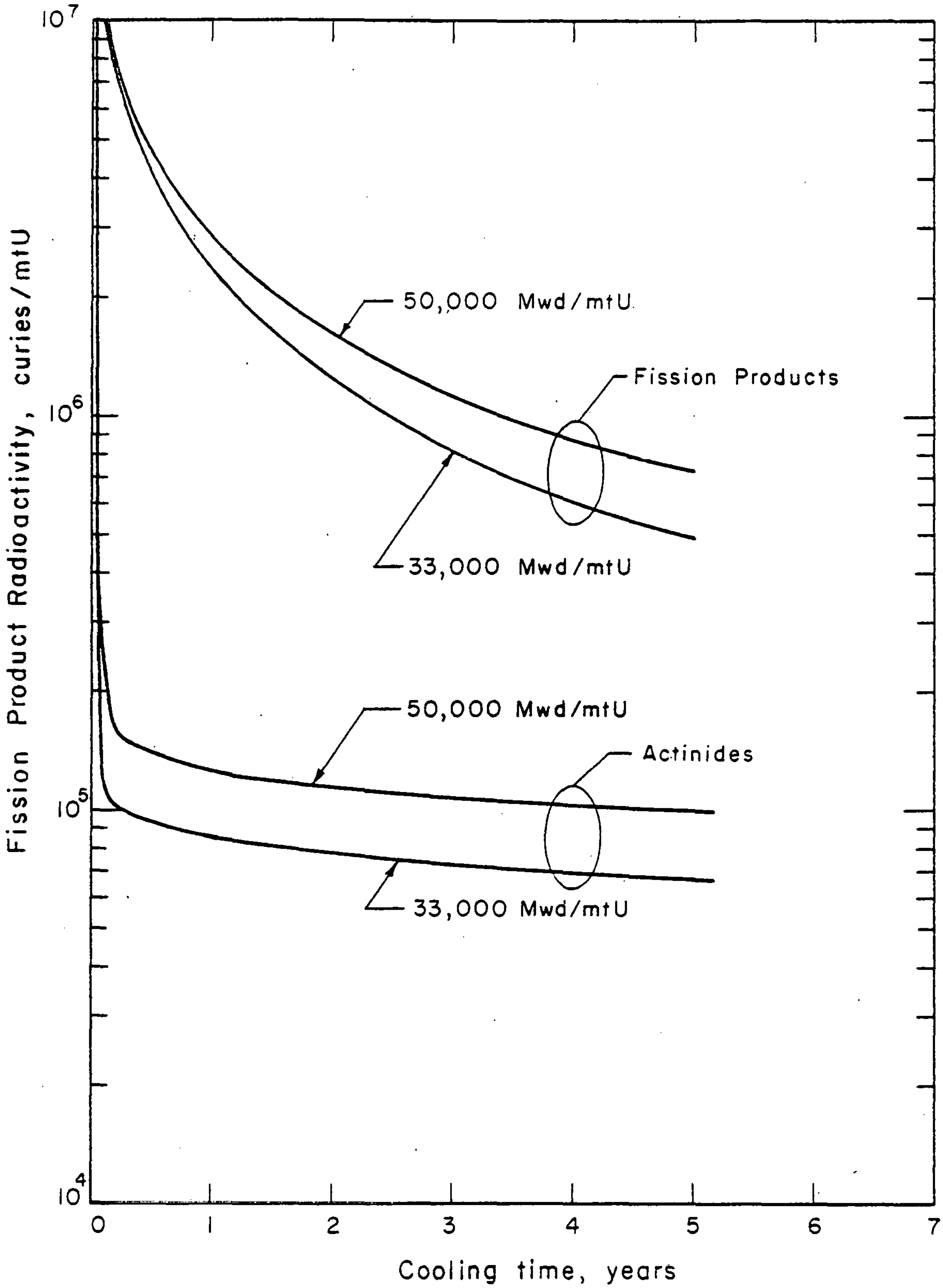

Fig. 6.3 Actinide and fission product radioactivity in PWRs with fuel of 33,000 Mwd/mtU and 50,000 Mwd/mtU fuel burnup.

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