OPTIMIZATION OF TIME AND LOCATION DEPENDENT SPENT NUCLEAR FUEL STORAGE CAPACITY

by

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Dissertation submitted to the Graduate Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Nuclear Science and Engineering

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March, 1977

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ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. H. A. Kurstedt and Dr. J. A. Nachlas for suggestions during the course of this work and editorial assistance in this publication.

Support during initial stages of this effort provided by the Mechanical Engineering Department of the Virginia Polytechnic Institute and State University, headed by , is gratefully acknowledged. The author is also indebted to for many hours spent typing this dissertation.

Finally, the author wishes to express deep feelings of appreciation to his wife for her patience, understanding and support, which were indispensable to the completion of this project.

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1. INTRODUCTION

1.1 The Controversy

Motto: "Even if we can't kill nuclear power we can stall it till it drops dead of its own economic weight," Chris Thomas, an anti-nuclearist.(1)

According to Greek mythology, Prometheus, the son of Titan Japet and brother of Atlas, created a man from lime. Wishing to animate him, Prometheus stole fire from heaven. To punish Prometheus, Zeus had him enchained by Hephaistos on the Caucasian mountains. As an eagle was devouring his liver, Prometheus was eventually rescued by Heracles.

The nuclear energy business in the U.S. today is in a situation not dissimilar to that of Prometheus awaiting his Heracles. Serious questions are being raised about the production of nuclear energy. The failure of the industry to develop publicly acceptable safety standards for nuclear plants, reprocessing facilities, waste management alternatives, and the plutonium recycle has created uncertainties that have not only retarded industry growth but also put nuclear energy production in jeopardy.(2) The recent growing concern with the state of the environment, which has led to a critical reevaluation of energy producing technologies, compounded with regulatory indecisions has led to nuclear power becoming a fierce battleground of proponents and opponents of this advanced technology.

The source of controversy is concentrated at the back end (post-reactor) of the nuclear fuel cycle. The back end of the cycle is where the highly radioactive spent nuclear fuel is discharged with the intent that it be reprocessed. Through reprocessing, unspent uranium and newly formed plutonium are recovered in order to recycle them back into the nuclear fuel stream. Radioactive-waste generation during reprocessing and plutonium radiotoxicity with the possibility of its diversion for fabrication of atomic weaponry are two major issues receiving attention by regulatory agencies and the public.

It has been suggested that the current opposition to nuclear power has much in common with other social protests of the past two decades, but differing in fundamental respects. The protest deals with a subject rooted in science and technology and it grows primarily out of fear: fear of guerilla-inspired terrorism and sabotage, fear that other nations may buy nuclear plants from the U.S. and then use them to make nuclear weapons, fear of cataclysmic nuclear plant accidents -- in short, fear of destruction of life and property.[1,2]

Justification of those fears is certainly open to debate. The nuclear industry has 60 nuclear power plants producing about 8% of all U.S. electricity today.[3] It has demonstrated that it has the ability to provide relatively inexpensive electrical energy with a reasonable guarantee of safe operation of nuclear power plants. Nuclear energy, when compared with other energy sources, appears to be one of the most economically viable alternatives for satisfying growing energy demand over the next several decades.

1.2 The Problem

The most serious current problems of the nuclear industry occur at the back end of the fuel cycle. The present standstill of reprocessing in the U.S. and uncertainties about adequate reprocessing capacity in the near and longer-term future have resulted from lack of definitive governmental regulatory policy with respect to plutonium recycle and waste management. Spent-fuel assemblies, presently accumulating in spent fuel storage basins at the reactor sites, cannot be removed for disposal; and, thus, the fuel cycle cannot be closed until a regulatory policy is determined with respect to spent fuel. The current nuclear fuel cycle issues have had a major impact on fuel cycle economics. At the Atomic Industrial Forum (AIF) Fuel Cycle Conference in 1975, Bertram Wolfe has summarized: "From an economic standpoint, the issue at the back end of the fuel cycle has changed from one of maximizing its profitability to one of determining the most economic disposition of spent fuel -- and net result, overall, is increased cost to the fuel cycle."(4)

The lack of reprocessing capability (capacity and availability) in recent years has resulted in present and foreseeable spent fuel storage shortage. Recently, a number of publications identifying the problem have appeared in the nuclear industry literature. In the years 1975 and 1976, the Energy Research and Development Administration (ERDA) conducted a survey to assess existing on-reactor-site and off-site storage capabilities over the 1976-1983 timeframe.(5) The spent-fuel disposition capability was assessed by direct contact with all segments of the nuclear industry. The published projections of spent fuel storage capability in the next decade were based upon information furnished through questionnaires which were provided to 75 utilities by the Edison Electric Institute (EEI). The report indicates that even with timely implementation of the existing storage pool expansion plans there would be some reactors with insufficient fuel disposition capability. Reactor shutdown will occur from filled storage basins unless increases in storage capacities can be accomplished. It was found that, with no reprocessing available in 1983, about 69 reactors would not have space available to permit scheduled spent-fuel discharges and about 122 reactors would be operating without a full core reserve (FCR).

An analysis by Nuclear Assurance Corporation[(6)] also points out that if the reprocessing license applications are delayed until 1978, it will be necessary to accommodate close to 1950 fuel assemblies by 1980 and over 7800 assemblies by 1983. If storage facilities are not provided for these assemblies, it is estimated that about 23 nuclear power plants would be forced to shut down by August 1979 and about 50 by August 1983.[(6)]

A potential shortfall in announced reprocessing capacity is indicated in a number of publications.[(7,8,9)] Wolfe in his paper presented at the AIF Fuel Cycle Conference, 1975, has estimated that even if the Allied General Nuclear Services (AGNS) reprocessing plant would start-up in 1978 and both the Nuclear Fuel Services plant and planned Exxon reprocessing plant would become operational in 1980 and 1984 respectively, the additional spent-fuel storage requirements would reach about 15,000 MT by 1990.[(4)]

A more immediate problem consists of the currently operating power plants which are losing fuel storage pool capacity for full core discharge. About 12 nuclear power plants will experience a storage capability shortage in the near-term future.[10] For example, the Palisades and Big Rock Point plants (Consumer Power Company) currently cannot discharge a full core. It is estimated that Oconee units 1 and 2 (Duke Power Company), Dresden 1 (Commonwealth Edison), Robinson unit (Carolina Power & Light), and Nine Mile Point 1 (Niagara Mohawk Power Corporation) will lose full core discharge ability in the period 1977-1978.[10]

Some strategies for moderating the spent-fuel storage problem in the near term have been suggested. Among those which currently involve NRC review and approval are:[11]

1. expansion of fuel storage capacity, through spacing modifications, at the spent-fuel storage pools of operating reactors and at the existing storage sites of the reprocessing plants of Nuclear Fuel Services and General Electric,
2. use of the spent-fuel storage basin at the Allied General Nuclear Services Barnwell plant prior to operation of the reprocessing facility,
3. construction and operation of independent spent-fuel storage facilities, and
4. transfer of spent fuel from one reactor storage pool to another where additional capacity exists.

Careful planning and execution in bringing additional spent-fuel storage on line will be required. The literature addressing the spent fuel storage problem has identified the problem of storage capacity shortage and has attempted to quantify that shortage under certain assumed scenarios of reprocessing capability over time. It is apparent that an investigation of spent-fuel storage expansion cost effective strategies, using Operations Research methodologies, is required.

1.3 The Approach

The spent-fuel storage problem involves the interaction of the generation of spent fuel, the time and location dependent spent-fuel storage inventories, and the demand for spent fuel. Interim spent-fuel storage must be considered as a fuel cycle option before profitable final spent fuel disposition is realized.

Spent-fuel storage facilities can be divided into two classes with respect to the location of spent-fuel sources: the on-site and off-site storage facilities. The on-site storage facilities are fuel storage pools which are part of the nuclear power plant complex.

These storage facilities can be expanded by the installation of redesigned, high-density fuel rack arrays and/or by modifications of the physical dimensions of the fuel basins.[8,12] Environmental and economic considerations may also lead to construction of off-site storage pools located at some central sites. Use of storage facilities at the reprocessing plants and their expansion may also contribute to the solution of the spent-fuel storage problem. The shutdown of nuclear power plants is clearly an infeasible solution to the spent-fuel storage problem. The total spent-fuel inventory, resulting from a balance between spent-fuel supply and demand, should at least be matched at all times by on- and off-site fuel storage capability.

The spent fuel storage capacity expansion problem is a time-dependent decision problem reflecting uncertainties in the growth of nuclear power capacity, spent-fuel demand, and availability of spent-fuel reprocessing and/or disposal. The spent-fuel storage capacity expansion decision problem rests upon two key elements:

1. the time at which a particular decision has to be made, and
2. the determination of the conditions upon which a decision has to be based.

It is necessary to determine cost effective storage expansion strategies constrained by regulatory policy. These policies are reflected in restrictions upon nuclear capacity growth and fuel cycle options. The key to the successful optimization of this complex system is the development of a computer oriented information system which reflects the time varying nature of nuclear fuel cycle operations. For this system an appropriate mathematical model has to be developed.

The objectives of this study are:

1. the identification of the key elements defining the

spent-fuel storage problem,

2. the development of an appropriate optimization model describing the spent-fuel operational system behavior and its performance criterion,
3. the implementation of a flexible computer-oriented information system incorporating the developed mathematical model, and
4. the determination of cost-effective strategies for spent-fuel storage capacity expansion over time in view of the projected nuclear capacity growth and spent-fuel disposition capability.

The dissertation comprises nine chapters. Additional introductory material on the fuel cycle and the present status of the U.S. reprocessing industry is presented in Chapter 2. A quantitative examination of the essential elements defining the spent-fuel storage problem is presented in Chapter 3. Potential revenues which may be realized by the recycle of fissile isotopes recovered from spent fuel as a result of reprocessing are considered in Chapter 4. A multistage dynamic spent-fuel storage model is developed and the choice of the optimization method -- a linear programming algorithm -- are discussed in Chapter 5. A summary of data in the actual application is presented in Chapter 6. Chapter 7 presents optimization results and Chapter 8 conclusions. Recommendations for further development of the model are presented in Chapter 9.

1.4 The Results

A large volume of significant results are presented in Chapter 7. These results may serve as a solid foundation upon which economically effective spent-fuel management decisions can be made. The principal results are summarized below:

1. A spent-fuel storage capacity expansion plan should be such that spent fuel-storage requirements are satisfied at all times while a full core discharge capability is maintained.
2. The results show that spent-fuel storage capacity has to be expanded beyond the provisions of the currently planned storage expansion program.
3. With respect to the alternatives of spent-fuel storage on the reactor sites or off-site, the results indicate that the on-site storage capacity expansion is economically preferable to storing the spent fuel away from the reactor.
4. The results also show a definite advantage in timely expansion of the on-site storage capacity in excess of the current spent-fuel storage needs.
5. The optimal storage capacity expansion plan is very sensitive to the timing of the reinitiation of the reprocessing activity.
6. The results of this dissertation indicate that if the reprocessing activity with the planned capacity is not

aggressively actuated before mid-1982, the back end of the fuel cycle would become an economic liability. An extended delay will result in spent-fuel storage expenditures higher than the profit realized by the nuclear fuel recycle.

2. BACKGROUND OF THE SPENT FUEL STORAGE PROBLEM

Before concentrating on the specifics of developing spent-fuel storage by location over a given time horizon, it is necessary to outline the position of this problem within the entire fuel cycle environment. The nuclear cycle description with a more detailed review of the spent-fuel disposition alternatives, commonly referred to as the "back end of the fuel cycle," are presented in this chapter. A brief discussion of the spent-fuel storage alternatives is presented here in preface to an in-depth analysis of the physical attributes of the problem which are examined in Chapter 3. The entire nuclear fuel cycle is in a state of flux; hence many uncertainties, which are constraints on the cycle, are discussed.

2.1 Physical Description of the Fuel Cycle

The light-water reactor fuel cycle consists of the sequence of operations performed to process the nuclear fuel from the uranium ore through the reactor and to eventual disposal. The individual steps involved in the nuclear fuel cycle are depicted in Figure 2.1. The fuel cycle operations involve mining and milling of ore, conversion of U_3O_8 to UF_6, enrichment, conversion of UF_6 to UO_2, fuel fabrication, irradiation in a reactor, spent-fuel storage, reprocessing, and waste management.

A major portion of domestic uranium ore can be found in New Mexico, Wyoming, Colorado and Utah. The assay of uranium ore

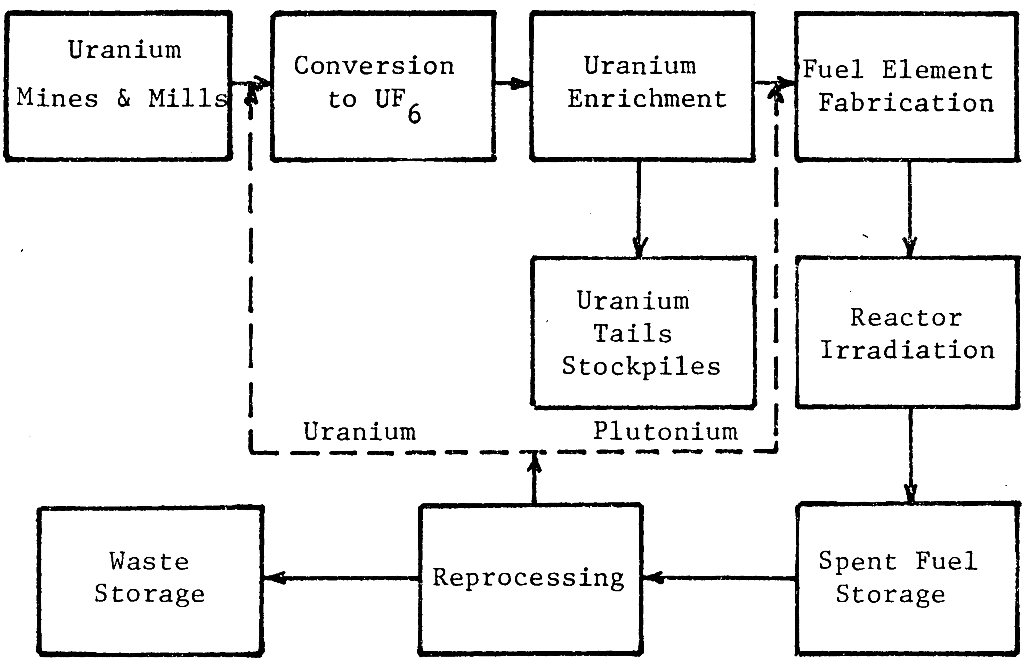


Figure 2.1. LWR Fuel Cycle.

averages about 0.2% or 2 kg of U_3O_8 per ton of ore.[13] A uranium mill extracts uranium from the ore by mechanical and chemical processing of the mineral into a semi-refined product, commonly called "yellowcake" which contains 70 to 90% U_3O_8. The U_3O_8 concentrate extracted from the ore is then converted to the volatile compound uranium hexafloride (UF_6) for enrichment by the gaseous diffusion process. This process separates the natural uranium feed stream in the form of UF_6 into two output streams: enriched product and depleted uranium tails. The uranium tails, whose uranium-235 assay is about 0.2%, have to be stored. Isotopic enrichment of uranium is necessary to provide fuel for a light-water-moderated nuclear power reactor. The required content of uranium-235 in nuclear fuel for the current generation of reactors is from 2.5 to 4%. The remainder of nuclear fuel consists almost entirely of the fertile isotope, uranium-238. In a fuel fabrication plant UF_6 is converted to UO_2. Pellets of UO_2 are formed and sintered to the desired density and then loaded into zircaloy or stainless steel tubes. The tubes (fuel elements) are assembled into fixed arrays to be handled as fuel assemblies. Principal physical characteristics of both Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) fuel assemblies are listed in Table 2.1. Fresh fuel assemblies can be temporarily stored, inspected and tested prior to use. The assemblies then are placed in the reactor core and burned. During residence of the nuclear fuel in the reactor, uranium-235 nuclei are fissioned, giving off energy. The fission process is accompanied by the

Table 2.1: Description of Typical LWR Assemblies[14]

Characteristics	PWR	BWR
Overall length [m]	4.059	4.470
Fuel element length [m]	3.851	4.064
Cross-section [cm]	21.4 x 21.4	13.9 x 13.9
Fuel element OD [cm]	0.950	1.252
Fuel element array	17 x 17	8 x 8
Fuel assembly weight [Kg]	668.6	279
Uranium/assembly [Kg]	461.4	188.7
Zircaloy/assembly [Kg]	129.7	56.7
Hardware/assembly [Kg]	15.5	8.2
Total metal/assembly [Kg]	145.2	64.9
U-235 assay	2.73*	3.21*

Note: *Reference WASH-1139 (74)[15]

production of a variety of elements, many of which deplete the neutron population needed for maintaining the fission reaction. When the uranium-235 content has diminished to about one per cent, fission product poisoning and reduced content of uranium-235 make it necessary to partially refuel the reactor.

In PWR reactors, about 1/3 and in BWR reactors, about 1/4 of the fuel elements have to be replaced annually. In addition to residual uranium-235, spent fuel contains about 0.7 per cent fissile isotopes, plutonium-239 and plutonium-241. The genesis of plutonium in a LWR reactor is described in Appendix 1. Fissile plutonium, generated in partially burned LWR fuel, is even more fissionable than uranium-235 and participates in a fission reaction. The approximate LWR spent fuel discharge characteristics for the current generation nuclear units with a rating of about 1,000 MWe and a capacity factor of 75% are shown in the Table 2.2.[16] Data shown in Table 2.2 are based upon the assumption that the discharged fuel has achieved its full design exposure, which probably is overly optimistic. Hence, the uranium-235 enrichment of the spent fuel may be slightly higher and the plutonium concentration slightly lower.

Storing of spent fuel is the first activity related to the fuel element after its irradiation in the reactor. In addition to uranium and plutonium, spent fuel contains a variety of fission products. Most of the fission products are radioactive and provide the chief source of heat and radiation from spent fuel. During the storage period, the radioactivity and heat output decreases approximately

Table 2.2: Discharged LWR Spent-Fuel Characteristics[16]

Type of plant, 1000 MWe	PWR	BWR
Amount of discharged fuel, [MT]	29	35
Amount of U-235 in recovered uranium, [Kg]	248	272
U-235 assay, per cent	0.89	0.81
Amount of Pu-239 and Pu-241, [Kg]	194	232

according to the law $t^{-1.2}$, where t is the time after removal from the reactor. Most of the fission product decay occurs shortly after the discharge, but cooling for about 120 to 180 days is required in order to assure safety during spent-fuel transportation and reprocessing.(17) The cooling period is determined primarily by the volatile iodine-131, with half-life of 8.14 days, which, through its decay, is removed as a problem in reprocessing.(18)

Alternatives for managing spent fuel include the storage of unpackaged fuel in water-cooled basins or air-cooled vaults where reprocessing is not expected to be delayed more than 10 to 20 years. Storage of packaged spent fuel in water-cooled basins, air-cooled vaults, concrete surface silos, stable geologic formations, or near surface heat sinks, can be contemplated under circumstances where reprocessing would be expected to be delayed beyond 10 to 20 years.(14) In this alternative, packaging of spent fuel consists of sealing the fuel assembly inside a container after filling the container with a solid or gaseous heat transfer medium. After cladding, the package is a second barrier for the confinement of fission products.

A detailed description and evaluation of the merits of different spent fuel storage concepts is beyond the scope of this dissertation. An authoritative survey of the storage concepts for spent fuel and other radioactive wastes exists in the literature.(14)

Following storage for cooling, the spent fuel is shipped in a special container to a reprocessing facility to reclaim usable fissile material and concentrate the radioactive fission products. In general, reprocessing consists of three steps: head-end treatment, solvent extraction, and product purification. During head-end treatment fuel elements are chopped into short sections and fuel material is dissolved out by nitric acid. Uranium and plutonium are extracted from the acid solution by a process using an organic solvent. The process adopted in the U.S. employs tributyl phosphate (TBP) dissolved in a kerosene-like hydrocarbon as the separating agent, (Purex process).[18,19] The chemical separation process is based upon the fact that when uranium and plutonium ions are in a highly electron-defficient state (i.e., they are highly oxidized) they are more soluble in the organic solution (TBP) than in an acid aqueous solution. On the other hand, under the same conditions,the fission products are more soluble in strongly acid aqueous solution than in TBP. Through countercurrent mixing of organic and acid aqueous solutions in vertical columns or centrifugal contactors, the substances more soluble in one solution than in the other can be efficiently separated.

Upon discharge from the reprocessing facility, radioactive wastes have to be solidified into an insoluble, non-leachable form.[20] The solidified waste is packaged and placed in permanent repositories. The principal fission products in aged high-level wastes are cesium-137 and strontium-90. Wastes also contain traces of plutonium. Since plutonium is a valuable product, its waste content is kept at a minimal value. Typically, the plutonium content in the wastes is less than 0.1

per cent.[19] Cesium-137 and strontium-90 have half-lives of about 30 years; therefore the storage time during which the waste would become inocuous may span several centuries.

Presently, the form of the waste and the method of its disposal require decisions on part of the government.[20] Waste storage in geologically stable formations, (for example, bedded salt formations) is being considered as the best compromise between storage safety and societal responsibility for radioactive waste management.[21]

The uranium and plutonium recovered through reprocessing may be used as additional nuclear fuel. It was estimated that by 1990, uranium recycled back into the fuel stream would result in a savings of about 11% in natural uranium resources and about 1% in separative work.[22] In addition, plutonium recycle would add another 9% in natural uranium and 11% in separative work savings.[22]

2.2 Current Uncertainties in the U.S. Nuclear Fuel Cycle

The current generation of electricity from nuclear fuels is influenced by important uncertainties which have impact upon the entire fuel cycle. An attempt is made here to enumerate some of the most important uncertainties and discuss briefly their mutual interaction.

According to a study by the Energy Research and Development Administration (ERDA),[23] the uncertainties influencing the front end of the fuel cycle relate primarily to the availability of uranium resources and the enrichment capacity to support the Light Water Reactor (LWR) industry after 1983. The amount of electricity supplied by nuclear power is expected to grow from about 8.0% (50,000 MWe) today[3] to 30% of the electricity production in 1985 and 52% of electricity generating capacity by the year 2000.[22]

The projected cumulative demand for uranium at 0.30% diffusion plant tails assay is projected to rise steadily from about 161,000 short tons in 1980, 397 thousands tons in 1985, and 814 thousands tons in 1990 to 2,187,000 tons in the year 2000.[15] These projections assume a continued improvement in regulatory processes from the nuclear industry point of view and a continuation of current trends in demand for electricity with a long-term program of energy conservation measures enforced, (Scenario D, WASH-1139 (1974)). The domestic reserve estimates as of January 1, 1976 indicate potential uranium reserves of about 3.8 million tons with a maximum production cost of $30 per pound of U_3O_8. Of these reserves, 780,000 tons are assured and 3 million are estimated; including probable reserves of about 1,060,000 tons, possible reserves of 1,270,000, and speculative 590,000.[24] Even though the probable additional uranium resources that are necessary to support the projected LWR program exist, the lead time for discovery and construction of production facilities is long, and rapid expansion of exploration effort is necessary.[25]

Also, it is not clear how adequate enrichment capacity will be supplied to support the nuclear industry beyond 1983. It is projected that about 7 new enrichment plants of an 8.75 million SWU per year capacity will be needed between 1984 and 2000 for the U.S. nuclear power market.[26] Processes at the front end of the fuel cycle are highly investment-intensive with lead times ranging from eight to ten years.

The most significant current uncertainties requiring urgent solution by regulatory agencies are those which influence the back end of the fuel cycle. These uncertainties, resulting from a lack of definition or committment to realistic acceptance criteria by regulatory agencies, relate primarily to plutonium recycle, safeguards, and waste management. Also,the issue of radioactive material transportation has not been resolved.[20] On August 21, 1974 the Atomic Energy Commission (AEC) issued for comment a draft report entitled "Generic Environmental Statement-Mixed Oxide Fuel (GESMO)." The recycle issue and the Nuclear Regulatory Commission's (NRC) view regarding this issue have created difficulties in closing the LWR fuel cycle in the U.S.[27] The delay in the final issuance of the Environmental Statement, which was published in August 1976 under the title GESMO-1, has adversely influenced the licensing of construction permits for the reprocessing plants and the mixed-oxide fuel fabrication plants. This has resulted in a delay in the initialization of plutonium recycle. Currently, the GESMO issue is in a public hearing process.[28]

At present the U.S. reprocessing capacity, consisting of three reprocessing facilities, has been brought to a standstill by regulatory uncertainties. This has prevented the industry from making necessary plans for implementing required programs to close the fuel cycle.

The West Valley, N.Y. reprocessing plant, which is operated by Nuclear Fuel Services, has reprocessed 630 tons of spent fuel since April 1966 with radiation exposures of up to 32,000 megawatt-days per metric ton of uranium. The plant was shut down in 1972 in order to implement modifications that would increase the plant capacity from 300 tonnes per year to 750 tonnes per year. One of the principal modifications(16) was the addition of the second solvent extraction cycle for plutonium. Other planned modifications include a new facility for the conversion of uranium nitrate to UF_6, facilities for storage and solidification of high-level radioactive wastes, measures to meet safety criteria for protection against severe natural phenomena such as tornadoes and seismic disturbances, and equipment to solidify the plutonium nitrate into PuO_2 to satisfy new transportation rules for plutonium. Initial documents to support the new facility's construction permit were submitted in October 1973. At last reports, the estimated cost of modifications had risen to about $600 million, and Nuclear Fuel Services has announced that the West Valley reprocessing plant may never be reopened.(29)

The second of the reprocessing plants is the Midwest Reprocessing Plant, operated by General Electric Company (GE). This plant was expected to provide 300 tonnes per year of reprocessing capacity. The Morris plant incorporated major departures from the typical Purex-TBP process. The General Electric wet-dry Aquafluor process involved TBP solvent extraction for the separation of uranium and plutonium from the fission products, ion exchange for separating uranium and plutonium from each other, and fluidized beds for the calcination of uranyl nitrate to the oxide (UO_2) and for the conversion of the oxide to the hexafluoride (UF_6). Instead of the second extraction cycle for uranium, a separation step was incorporated that exploited the differences in volatility for separating the fluorides of the fission products from the UF_6.[19] Since this step included the remote handling of radioactive powders, the problems were far greater than anticipated. Due to these technical difficulties with the wet-dry extraction process, GE announced in July 1974 that the plant was inoperable in its present form and that extensive modifications would be required if the plant were to operate commercially. The total investment incurred to date by the GE plant has been $60 million. The modifications would require another $90 to $130 million and a minimum of four years to complete. The eventual outcome of this reprocessing venture will depend upon the results of a study which GE expects to complete in 1976.[4,27]

The third reprocessing plant, the Barnwell Plant operated by Allied General Nuclear Services, did not reach its goal to start operation in 1974; and while construction is complete, the plant is still not operating. The plant is to provide 1,500 tonnes per year of reprocessing capacity. The separation and UF_6 conversion facilities were complete at the end of 1975. The lack of definitive regulations governing plutonium and waste material conversion for transport have put the continuation of the design work of the plutonium processing facility in jeopardy. The most optimistic estimate for a decision in this highly sensitive area of waste treatment and plutonium use is 1977.[16]

A newcomer to the reprocessing field is Exxon Nuclear Co., Inc. which has filed an application with the Nuclear Regulatory Commission to build a reprocessing plant at Oak Ridge, Tennessee. The plant would provide 1,500 tonnes per year of reprocessing capacity, later achieving a 2000 tonnes per year limit. The earliest date for completion is 1984.[4]

The deferral of plutonium recycle due to either licensing and/or economic constraints is creating another problem: the on-going growth of a spent-fuel stockpile.

3. QUANTITATIVE EXAMINATION OF THE ELEMENTS OF THE SPENT FUEL STORAGE PROBLEM

In this chapter the principal elements of the spent-fuel storage problem are examined in detail. A background is given on spent-fuel supply projections, reprocessing capacity forecasts, and spent-fuel disposal alternatives. Also spent-fuel storage capability and related spent-fuel transportation considerations are discussed. This detailed analysis is provided in order to identify principal physical attributes and economic factors of the spent-fuel storage problem. Chapter 4, where spent-fuel value is discussed, complements the analysis presented in this chapter. On the basis of quantitative examination, a spent-fuel storage model, which is presented in Chapter 5, is developed. Data and cost parameters used in the actual application of the spent-fuel storage model are summarized in Chapter 7.

3.1 Spent Fuel Supply Projections

Time dependent spent-nuclear-fuel generation rates for each of several types of nuclear power plants can be estimated on the basis of annual discharge rate and installed capacity. The types of nuclear reactors that will comprise the nuclear capacity in the U.S. for the remainder of the century may include light-water reactors (LWR), high-temperature-gas-cooled reactors (HTGR) and fast breeders. The fast breeder is expected to be introduced in the early 1990's.[15] The HTGR has been assumed to penetrate the nuclear market to the extent of about 10% of added nuclear capacity in the early 1980's, increasing to 15% of the thermal reactor additions by the late 1980's, and remaining at that level for the rest of the century.[15] These projections could well be reduced as a result of the action by Gulf General Atomics in terminating HTGR sales.[30] The reactor type contributing most to the spent-fuel storage problem is the light-water reactor because its share of electricity generation from nuclear fuel is expected to continue at levels about 90% for the rest of this century.[15] The LWR's can be divided into two categories: Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR).

Usual fuel management practice for LWR's in operation today is that this type of reactor is refueled on an annual basis; however, a varying fraction of the fuel residing in the reactor core may be replaced during any refueling. This fraction depends on the power plant capacity factor for the preceding year. The capacity factor is defined as the ratio of actual power produced during a period to the power which could have been produced had the reactor operated at full rated power continuously throughout the period. The capacity factor value depends upon many factors. Among them are the age of the particular reactor design, experience of the utility in operating the reactor, and the length of time the plant has been in operation. Also, the plant's capacity factor depends upon its position in the order of merit of the utility system. In general, it is assumed that nuclear plants can operate for about 40 years. During the first year of operation the capacity factor is about 40%. In the following two years it increases to about 65%. During the 4th to 15th years of operation the capacity factor increases to about 75%. Beginning with the 16th year, it is estimated that the capacity factor decreases linearly 2% per year to a minimum of 25%.[(15)]

Recent projections show nuclear power growth up to the end of the current century. These projections are published in the ERDA report entitled "Nuclear Power Growth 1974-2000," WASH-1139 (1974).[(15)] In this report, nuclear power installation growth is projected under several scenarios differing in degree of optimism about the future trends in energy consumption and nuclear electricity generating capability. These long-term projections of nuclear power development are based on an assessment of population and economic growth. The population and economic projections are linked to a level of total energy resource consumption modified by such considerations as the effect of successful conservation measures, the potential for greater use of electricity in the economy, and the existence of energy supply constraints. The four scenarios developed in WASH-1139 (1974) are labeled A, B, C, and D.

Scenario A is the lowest forecast of nuclear power capacity. The assumption is made that delays in bringing nuclear plants on line will continue to plague the industry. The sources of delay are manifold including late equipment deliveries, construction delays, strikes, poor labor productivity, and regulatory problems. The time required to bring a nuclear power plant on line is assumed to consist of about two years for planning and design, license application, and environmental report preparation; two years for construction permit approval; and, six years for construction and start-up. In summary, this scenario indicates that the current trend toward slippage in reactor construction will continue unabated and that the long-term demand for electricity will be low.

Scenario B postulates continued improvement in the regulatory processes, fewer construction delays than at present, and unabated current growth trends in electricity demand. It also assumes some improvements over recent experiences in construction and regulation. Specifically, it is assumed that the time to bring a plant on line will average eight years with about 15 months for planning and design, license application, and environmental report preparation; 15 months for construction permit issuance; and, about five and one-half years for construction and start-up.

Scenario C assumes additional improvements in construction performance and regulatory processes. New legislation and regulations would permit construction to begin prior to completion of the construction permit application safety review. The site environmental statement would be completely separated from the safety review. This presupposes that standardized plant designs would be used in the license application. The project time would be about six years with one year for design and planning, license application preparation, and environmental review, and five years for construction and start-up with concurrent operating license review and approval. In short, this scenario assumes a marked improvement in construction time, relatively high future demand for electricity, and predominance of nuclear power over use of fossil fuel for new electricity generating power plants.

Scenario D assumes a general reduction in the growth of electricity use which for the near term means a reduction in non-essential and extravagant uses of energy. The reduction in electricity production in the near-term future is realized by reducing the number of oil and gas fired plants. In this view, while demand for energy is met, fewer resources are consumed because higher energy prices relative to other commodities cause industrial and other energy consumers to improve the efficiency with which energy is consumed. Other assumptions for this scenario are continuation of improvements in the regulatory process that fewer construction delays would be incurred. There is a common consensus in nuclear industry communications that Scenario D of WASH-1139 (1974) is a most plausible extrapolation of the current trends.(7)

Tables 3.1 through 3.4 and Figure 3.1 exhibit the above discussed scenario forecasts of LWR capacity installation. Tables 3.1 through 3.4 are based on data taken directly from WASH-1139 (74). The totals were added for this evaluation. In order to be able to deduce spent fuel generation from the nuclear electricity generating capacity projections, the following assumptions were made in this study:

1. Most of LWR units being built have ratings in the range of 800 to 1000 MWe.

Table 3.1. LWR Capacity Growth, Scenario A.[15]

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1976	29.8*	15.4*	45.2*
1977	41.9	17.5	59.4
1978	43.9	19.5	63.4
1979	48.0	23.3	71.3
1980	55.0	29.7	84.7
1981	76.5	36.6	113.1
1982	92.1	47.9	140.0
1983	113.5	55.0	168.5
1984	133.2	64.1	197.3
1985	149.7	71.9	221.6
1986	169.4	81.7	251.1
1987	190.1	91.0	281.1
1988	210.7	99.3	310.0
1989	231.7	109.8	341.5
1990	252.0	119.9	371.9
1991	273.8	130.8	404.6
1992	295.2	141.5	436.7
1993	315.7	151.8	467.5
1994	334.8	161.3	496.1
1995	352.0	169.9	521.9

Notes: *The values for 1976 are adjusted to the current status.[3]
The rest of the data are the same as in the reference.[15]

Table 3.1. (Continued)

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1996	370.0	178.9	548.9
1997	387.6	187.7	575.3
1998	404.6	196.2	600.8
1999	419.9	203.9	623.8
2000	433.5	210.5	644.0

Table 3.2 LWR Capacity Growth, Scenario B.[15]

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1976	29.8*	15.4*	45.2*
1977	41.9	18.3	60.2
1978	46.3	22.3	68.6
1979	53.1	27.3	80.4
1980	67.8	33.2	101.0
1981	88.3	43.3	131.6
1982	106.0	51.4	158.2
1983	119.6	61.6	181.2
1984	145.1	69.7	214.8
1985	167.7	79.9	247.6
1986	192.5	90.7	283.2
1987	217.8	102.3	320.1
1988	244.3	115.2	359.5
1989	273.8	129.9	403.7
1990	303.7	144.8	448.5
1991	335.0	160.5	495.5
1992	365.3	175.6	540.9
1993	396.3	191.1	587.4
1994	426.2	206.1	632.3

Notes: *The values for 1976 are adjusted to the current status.[3]
The rest of the data are the same as in the reference.[15]

Table 3.2. (Continued)

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1995	455.5	220.8	676.3
1996	483.1	234.6	717.7
1997	511.5	248.7	760.2
1998	538.1	262.0	800.1
1999	564.7	275.4	840.1
2000	589.8	287.7	877.5

Table 3.3 LWR Capacity Growth, Scenario C.[15]

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1976	29.8*	15.4*	45.2*
1977	43.9	20.3	64.2
1978	47.2	24.4	71.6
1979	56.5	29.7	86.2
1980	76.8	34.2	111.0
1981	94.8	47.0	141.8
1982	114.3	55.9	170.2
1983	133.5	67.5	201.0
1984	154.7	74.8	229.5
1985	175.5	84.7	260.2
1986	203.6	98.1	301.7
1987	237.1	113.4	350.5
1988	270.1	129.9	400.0
1989	306.9	148.3	455.2
1990	344.9	167.3	512.2
1991	382.3	186.0	568.3
1992	419.1	204.4	623.5
1993	456.0	222.8	678.8
1994	492.2	241.0	733.2

Notes: *The values for 1976 are adjusted to the current status.[3]
The rest of the data are the same as in the reference.[15]

Table 3.3. (Continued)

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1995	527.4	258.5	785.9
1996	561.4	275.5	836.9
1997	594.8	292.3	887.7
1998	626.5	308.1	934.6
1999	656.6	323.1	979.7
2000	683.9	336.6	1020.5

Table 3.4. LWR Capacity Growth, Scenario D.[15]

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1976	29.8*	15.4*	45.2*
1977	41.9	18.3	60.2
1978	46.3	22.3	68.6
1979	53.1	27.3	80.4
1980	67.8	33.2	101.0
1981	82.2	42.1	124.3
1982	100.5	50.3	150.8
1983	117.2	59.7	176.9
1984	140.6	68.3	208.9
1985	161.4	77.6	238.8
1986	184.0	87.3	271.3
1987	209.2	89.9	308.1
1988	233.5	110.6	344.1
1989	260.7	124.2	384.9
1990	289.0	138.3	427.3
1991	316.1	151.9	468.0
1992	343.9	165.8	509.7
1993	371.1	179.4	550.5
1994	398.3	193.0	591.3

Notes: *The values for 1976 are adjusted to the current status.[3]
The rest of the data are the same as in the reference.[15]

Table 3.4. (Continued)

Year	LWR Capacity [10^3 MWe]		
	PWR	BWR	Total
1995	424.2	205.9	630.1
1996	449.4	218.5	667.9
1997	474.3	231.0	705.3
1998	497.5	242.6	740.1
1999	519.6	253.7	773.3
2000	541.3	264.3	805.6

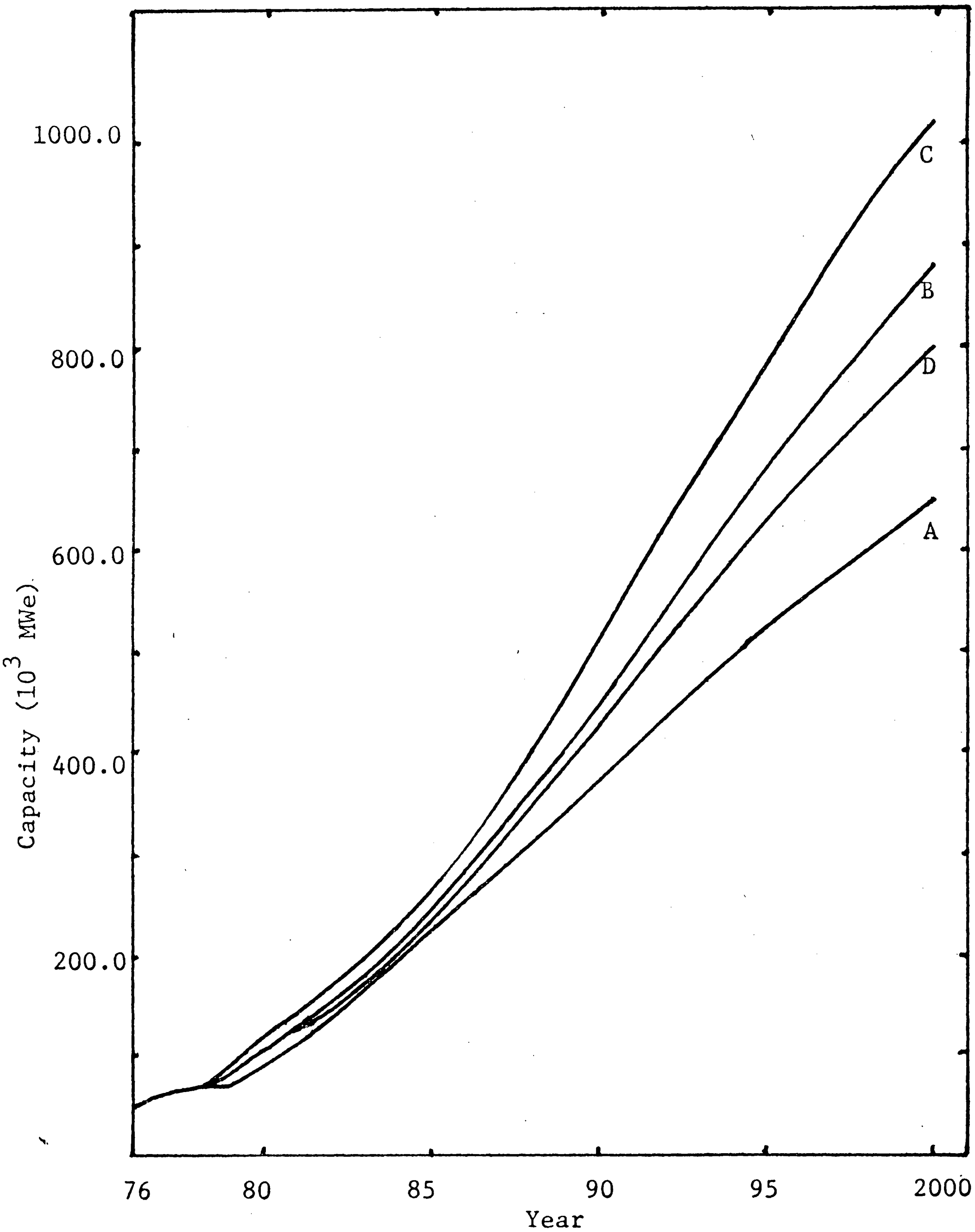


Figure 3.1. LWR Capacity Scenarios 1976-2000.

2. By analysis of PWR and BWR capacity growth over time it was found that the ratio of BWR to PWR capacity installed is about 1 to 2. This ratio was used to obtain a "typical" amount of spent fuel discharged annually per 1,000 MWe of LWR capacity. A capacity factor of 75% was used. The "typical"amount of annual spent-fuel discharge from 1000 MWe LWR was found to be about 30 MT.
3. Furthermore, some assumptions about the fuel management operation were necessary. It was assumed that the first discharge of spent fuel from a newly installed nuclear power unit occurs two years after its start-up.

Consequently, the amount of spent fuel discharged at a certain time is proportional to the nuclear capacity installed two years earlier.

Under assumptions (1) to (3), the annual spent fuel discharge rate and cumulative amount of spent fuel generated over time were estimated in this study. In order to evaluate the most recent trends in the spent fuel supply situation, these estimates were compared with data contained in ERDA-25, Edition 1976.[5]

In ERDA-25, results of a survey of spent-fuel disposition capability for the next decade have been published. The presented data are based on questionaires provided to 75 utilities by Edison Electric Institute (EEI). Only reactors built, licensed, under construction, or granted corporate approval up to the end of 1975 were included. The latest cancellations of nuclear plant orders and construction deferrals are accounted for in the report.

By comparison of the estimates derived in this study from WASH-1139 (1974) with the ERDA-25 spent-fuel supply projections, it was found that the recent order cancellations and slippages in nuclear power plants construction result in a decrease of about 8% in the WASH-1139 (74) Scenario D projected cumulative amount of discharged spent fuel in the years 1976 and 1977. This difference then decreases to 1.8% around 1980; and around 1985 it is around 15%. Table 3.5 shows the annual spent-fuel discharge rate and cumulative discharge over time. Up to 1985, data correspond to ERDA-25 projections. From 1985 to 2,000, the listed spent-fuel discharge quantities were estimated in this study on the basis of nuclear capacity installation projections according to the report WASH-1139 (74), Scenario D, reduced by a factor of 15%.

It also can be pointed out that spent-fuel discharge over time can be considered to be probabilistic due to uncertainties of the growth rate of nuclear power installations, uncertainties concerning capacity factors and failure rates of fuel elements.

3.2 Reprocessing Capability Forecast

Spent fuel, which is a by-product of electricity production from nuclear power plants, is generated in quantities proportional to the nuclear power generation capacity. The rate of accumulation of spent fuel results from the balance between spent-fuel supply and the rate

Table 3.5. The Estimated Spent Fuel Supply Schedule 1976-2000.

Year	Spent Fuel Discharge	
	Annual [MT]	Cumulative [MT]
1976	874.4	2239.6
1977	1117.5	3357.1
1978	1506.5	4863.6
1979	1773.8	6637.4
1980	2018.1	8655.5
1981	2223.0	10878.8
1982	2444.8	13323.6
1983	3220.6	16544.2
1984	3977.8	20522.0
1985	4376.3	24898.3
1986	5326.9	30225.2
1987	6094.5	36319.7
1988	6918.2	43237.9
1989	7856.6	51094.5
1990	8774.6	59869.1
1991	9815.0	69684.1
1992	10896.2	80580.3
1993	11934.0	92514.3
1994	12999.4	105513.7
1995	14037.8	119551.5

Table 3.5. (Continued)

Year	Spent Fuel Discharge	
	Annual [MT]	Cumulative [MT]
1996	15078.2	134629.7
1997	16067.6	150697.3
1998	17031.5	167728.8
1999	17985.9	185714.7
2000	18872.6	204587.3

of its final disposition. The rate of final disposition represents a demand on accumulated spent-fuel inventory. There are basically two modes of spent-fuel disposition: reprocessing of spent fuel with recovery of nuclear fuel material or disposal of spent fuel as a waste. The choice between these two alternatives depends upon many factors; among them are non-proliferation, economic constraints, availability of reprocessing capacity and other facilities supporting plutonium recycle, and spent fuel disposal capability. The current moratorium on plutonium recycle[31] and the unpreparedness of the government to accept waste in the form of spent fuel greatly increases the dimension of the spent-fuel storage problem. This situation is reflected in the statement made by H. T. Larson, Acting Director of NRC, at the Atomic Industrial Forum (AIF) Fuel Cycle Conference which was held in March 1975, Atlanta, Georgia:

"If plutonium is not recycled and reprocessing plants do not operate, spent-fuel elements, rather than solidified waste, may be transferred to ERDA facilities. The current situation is that only generic work is being conducted to establish a federal repository for high-level wastes."

Under the assumption of availability of both adequate reprocessing capacity and/or disposal facilities, the mode of final disposition of spent fuel will be determined by economic constraints. In order to justify reprocessing, the value of recovered products, uranium and plutonium, reduced by the cost of reprocessing must exceed the disposal cost. Under the current situation of zero "demand" on spent fuel inventories, the only alternative available to utilities is the interim storage of spent fuel. However, it is expected that reprocessing will be eventually reinitiated either to allow implementation of plutonium recycle in LWR's or to prepare adequate quantities of plutonium for the first generation of fast breeders. Spent-fuel reprocessing is of vital importance to a breeder economy, since that reactor is based upon plutonium fuel and does not have the flexibility of an uranium-235 alternate.[32] With the reprocessing and disposal capacity available, utilities will have to consider several options for spent-fuel management. The options such as temporary storage of spent fuel, reprocessing and storage of plutonium, or ultimate spent-fuel disposal will depend upon the status of the nuclear fuel industry in regard to future uranium and separative work prices and the availability of reprocessing. Also, other fuel cycle supporting services, such as nuclear fuel fabrication capability, is important. Forecasts of the future prices for nuclear fuel, and costs of the associated services are discussed in Section 3.3.

Demand upon spent fuel comes from availability of reprocessing and/or disposal capability. Report ERDA-25, Edition 1976, gives an estimate of spent-fuel reprocessing capability in the next decade. A summary of this estimate is presented in Table 3.6. In addition, Table 3.6 includes the projected capacity of the Exxon Nuclear reprocessing plant with capacity of 2000 MTU per year which is expected to come on line about 1985. A fourth reprocessing plant of 1500 MT of annual capacity, also included in the table was assumed to come on line about two or three years after the Exxon plant start-up. It was assumed that all planned reprocessing plants will reach their nominal capacity over a three-year period.

The regulatory aspects of plutonium recycle, which bear on the actual reprocessing schedule, are still not resolved and further delays may be expected. Hence, the expected reprocessing capability over time for the purposes of this study was considered under three scenarios in different degrees of optimism with regard to foreseeable delays in actual reprocessing plant start-up. Based upon a private communication,[10] three scenarios, which are arbitrarily labeled Optimistic, Realistic, and Pessimistic, were developed. It is assumed that the sequence of reprocessing capacity additions over time will remain the same for all scenarios; they will differ only by actual start-up date of reprocessing activity. The optimistic scenario assumes start-up of reprocessing in mid-1979. More conservative estimates, the realistic scenario, are that reprocessing will not be available before 1981. However, it is believed that reprocessing will be available no later than in mid-1983. This forecast has been labeled as pessimistic scenario. The total reprocessing capability under the three scenarios is summarized in Table 3.7.

The current standstill in reprocessing capability, which is described in Section 2.3, proves that the lack of reprocessing has a major impact on the economics of the back end of fuel cycle. Since reprocessing service is unavailable today, the actual cost of

Table 3.6. Reprocessing Plants Schedules.[5]

Year	Reprocessing Capacity [MTU]			
	AGNS	NFS	EXXON	4th Plant
1976	---	---	---	---
1977	---	---	---	---
1978	---	---	---	---
1979	375	---	---	---
1980	1125	---	---	---
1981	1500	350	---	---
1982	1500	750	---	---
1983	1500	750	---	---
1984	1500	750	---	---
1985	1500	750	750	---
1986	1500	750	1750	---
1987	1500	750	2000	500
1988	1500	750	2000	1500
1989	1500	750	2000	1500
1990	1500	750	2000	1500
----	----	---	----	----
2000	1500	750	2000	1500

Table 3.7. Reprocessing Capability Scenarios.

Year	Total Reprocessing Capability [MTU]		
	Optimistic	Realistic	Pessimistic
1976	----	0.0	0.0
1977	----	0.0	0.0
1978	----	0.0	0.0
1979	375	0.0	0.0
1980	1125	0.0	0.0
1981	1875	375	0.0
1982	2250	1125	0.0
1983	2250	1875	375
1984	2250	2250	1125
1985	3000	2250	1875
1986	4000	2250	2250
1987	4750	3000	2250
1988	5750	4000	2250
1989	5750	4750	3000
1990	5750	5750	4000
----	----	----	----
2000	5750	5750	5750

reprocessing is not known. W. A. Rodger, in his paper entitled "Throwaway fuel cycle" presented at the AIF Fuel Cycle Conference in Atlanta, Georgia, in March 1975 estimated LWR spent fuel reprocessing costs based upon current regulatory requirements which affect the design of reprocessing facilities. It was stated that the cost of the AGNS's Barnwell 5 MT/day plant, if it is completed, will exceed $600,000,000. Compared with the cost of the NFS 1 tonne/day West Valley plant, the capital cost of $35,000,000 is an increase by a factor of almost twenty.(33) Among the additional components of the Barnwell reprocessing plant design which have a major impact on reprocessing cost are the installation of a uranium nitrate (UNH)-to-uranium floride (UF_6) conversion facility and a plutonium nitrate ($Pu(NO_3)_4$)-to-plutonium oxide (PuO_2) conversion facility. On June 17, 1974, the AEC announced a ban on shipment of plutonium nitrate solution, effective June 1978.(27) In addition, the waste solidification facility, required for solidification of the liquid waste after interim storage, is included in the plant design. The interim storage is limited to five years.(34) The solid waste is to be shipped to a government operated and surveyed repository within ten years. The requirement that the present day reprocessing plants have to be designed to meet stringent tornado and seismic criteria had a major impact on the cost increase of the Barnwell plant.(33) Assuming that the ultimate cost of the Barnwell plant is about $600,000,000, the following estimates were made by W. A. Rodger.(33)

Fixed capital charges	\$100 per Kg
Operation	\$ 10 per Kg
Waste handling	\$ 50 per Kg
Safeguards	\$ 10 per Kg
Transportation	\$ 10 per Kg

An estimate of future trends in reprocessing costs was made by Larkin.[35] For the purposes of this study,the data were adjusted to reflect the current estimate given by Rodger which includes waste management and safeguards cost components.[33] Table 3.8 shows the reprocessing cost projections in which the shipping cost component (\$10 per Kg in 1976 dollars) was omitted. The shipping cost component, for the purposes of this study, will be included in another cost function of the model developed in Chapter 5.

3.3 The Spent Fuel Disposal Alternative

The economics of plutonium recycle have changed drastically over the past few years. Current uncertainties in government regulatory policies have resulted in construction delays in the supporting industries at the back end of the fuel cycle. This development compounded with the current cost trends of fuel cycle components has led to a consensus within the nuclear industry that the current value of the reprocessed uranium and plutonium may be essentially equal to the estimated reprocessing costs. Thus, the alternative of disposal of spent fuel as a waste, (throw-away or once-through-fuel

Table 3.8. Reprocessing Cost Trends

Year	1976	1980	1985	1990	1995	2000
Reprocessing Cost [$/KgU]	170.0	220.0	273.0	344.0	403.0	478.0

cycle), may be contemplated.(27,36) Spent fuel may be considered either as a waste or as a potential energy source subject to reprocessing. As a waste, spent fuel would be held in interim storage until transported for final storage or disposal. With a throw-away cycle, spent fuel would be stored in a reactor storage basin, if technically feasible with respect to basin capacity, or in an off-reactor-site storage facility for a period ranging from about five to ten years. The management of spent fuel while in interim storage is not unlike the management of solidified high-level waste.(36)

The current problems attendant to such storage are the provision of facilities and practices to assure continued cooling, adequate monitoring and surveillance to detect release of radioactivity from the containers, adequate treatment of effluents in the case of storage in pool-type storage facilities, no unauthorized entry or removal, and that faulty or failed containers can be replaced or overpacked.(14,21) Technical aspects of spent-fuel storage are described in detail in the literature.(14)

The costs for disposal of spent fuel as waste are unknown. The cost of spent fuel disposal would include components such as packaging, fission gas recovery, shipping to the permanent repository facility, and storage.(37) If it is assumed that the storage cost of spent fuel as waste will be proportional to heat generation only, then the cost would be similar to those of solidified high-level wastes from reprocessing. If, on the other hand, the costs would be proportional to volume, then the costs for disposal would be about five times higher than the cost for disposal of solidified high-level wastes.[27] Such waste costs have been estimated to be in the range of $20 to $50 per Kg of fuel for heat related costs and from $80 to $200 per Kg for volume related costs. A range for the negative value of spent fuel based on the concept of "once-through" fuel was estimated.[27] It was found that the range in negative (disposal) value of spent fuel in 1976 dollars is from $30 to $300 per Kg of fuel. A value of $100 to $150 per Kg is estimated to be most plausible.[27]

3.4 Spent-Fuel Storage Capability

Under conditions of an equilibrium closed fuel cycle, the operations related to spent fuel are the storage of discharged fuel elements at the reactor site for about four to five months to allow for decay of short-lived radioactive isotopes ("cooling"). For example, after irradiation at 35 MW/MTU of specific power and 25,000 MWD/MTU burn-up in the core of a LWR, a typical spent-fuel assembly has a total thermal power of 640 KW. After 120 days of cooling, the heat output decreases to about 8.5 KW per assembly.[14] After the discharged fuel assembly is cooled, it is shipped to a reprocessing plant where the unspent isotopes of uranium and plutonium are to be recovered and recycled back as nuclear fuel. The current lack of reprocessing capability and absence of definitive regulations concerning the output streams of the reprocessing plant such as waste management, plutonium safeguards and safety of plutonium use as nuclear fuel, has deferred spent-fuel reprocessing. Furthermore, current regulations prohibit spent fuel disposal. This status of the post-reactor fuel cycle indicates urgency to provide a longer-term spent fuel interim storage, (spent-fuel storage in an unpackaged form for periods shorter than 20 years).[14] In order to find the most economic way of storing spent fuel on an interim basis, an analysis of the alternative storage systems with associated expenditures is necessary. Two modes of spent-fuel storage and their associated costs will be analyzed here: on- and off-reactor-site spent fuel storage.

3.4.1 On-Reactor-Site Storage Systems

The currently designed nuclear power plant complex has an on-site storage facility for cooling spent fuel prior to its shipment to a reprocessing plant. The common design of a spent-fuel storage pool at the reactor site provides a capacity of 140% of full core load.[38] Full core loads for a LWR rated at 1,000 MWe are about 140 MTU for a BWR and about 100 MTU for PWR. The pool capacity can accommodate from three to four annual discharges of spent fuel and thus provides spent-fuel storage for about three to four years. This estimate implies that the reactor operator ignores the full core reserve (FCR) storage capacity which should be maintained for contingencies requiring full core discharge. For the case in which such capacity is needed, in the environment of an inadequate storage capacity situation, contingencies could result in a very costly extended down-time of the power plant. The requirement of having a full core excess storage capacity available at all times to be able to cope with such contingencies thus reduces the on-site storage capability to one or two years. For a reprocessing or disposal deferral period longer than two years, additional storage capacity is needed. A long-term interim storage capacity on the reactor site can be provided by two types of installations: expansion of spent-fuel racks in the existing and future reactor pools and by construction of additional independent pools adjacent to the reactor sites.

There is a certain flexibility in installing additional capacity to reactor pool basins. An extra capacity can be acquired by installing additional racks in the spare pool areas if needed. Also additional capacity can be obtained by enlarging the physical dimensions of the existing pool and/or by replacing the pool fuel assembly racks with standard spacing of 21 inches on centers for the fuel assemblies with racks with closer spacing. There is also the possibility of expanding existing capacity by using a two tier storage system.[8] This system makes use of top or side loaded racks mounted above the existing racks. Shielding requirements in this case may be reduced by storing "cold" fuel in the upper tier. Pool modifications involved in this system are limited primarily by economics, by pool structure, or by pool cooling capacity.

Fuel pool design including modifications must conform to required standards in order to guarantee safe operation of the pool.[39,40,41] It is required that the fuel element configuration must assure subcriticality with a K_{eff} of less than 0.95 under normal operation and also in accidental situations such as a fuel drop accident.[42] Criticality analysis of spent fuel arrays is usually performed using a two-dimensional diffusion code such as CITATION.[43] Input cross-sections for these calculations can be generated using a cell calculation code such as LEOPARD.[44] Fuel spacing effects for a stainless steel PWR rack are illustrated in Figure 3.2.[8] The upper and lower bounds are shown to reflect the influence of approximations made to treat the non-lattice water in generating the cross-sections.

Fuel rack design must also accommodate functional requirements for pool operation. The individual fuel element cells must be accurately aligned and manufactured to a tolerance which will allow placement and removal of fuel assemblies without physical damage to the fuel. Fuel rack structure must also maintain functional integrity through a seismic loading with respect to criticality.[8]

With the installation of high-density fuel racks into existing storage pools, the heat removal system must be reviewed with respect to increased heat load from additional stored spent fuel. Since older batches of fuel do not generate as much heat input as the newly discharged fuel, the extra cooling capacity may not be required. Many pool cooling systems were designed for spent fuel heat output, assuming an infinite irradiation period in the reactor and not correcting for finite irradiation. Hence, it is estimated that a margin in cooling capacity exists which may accommodate heat load from additional fuel.[8]

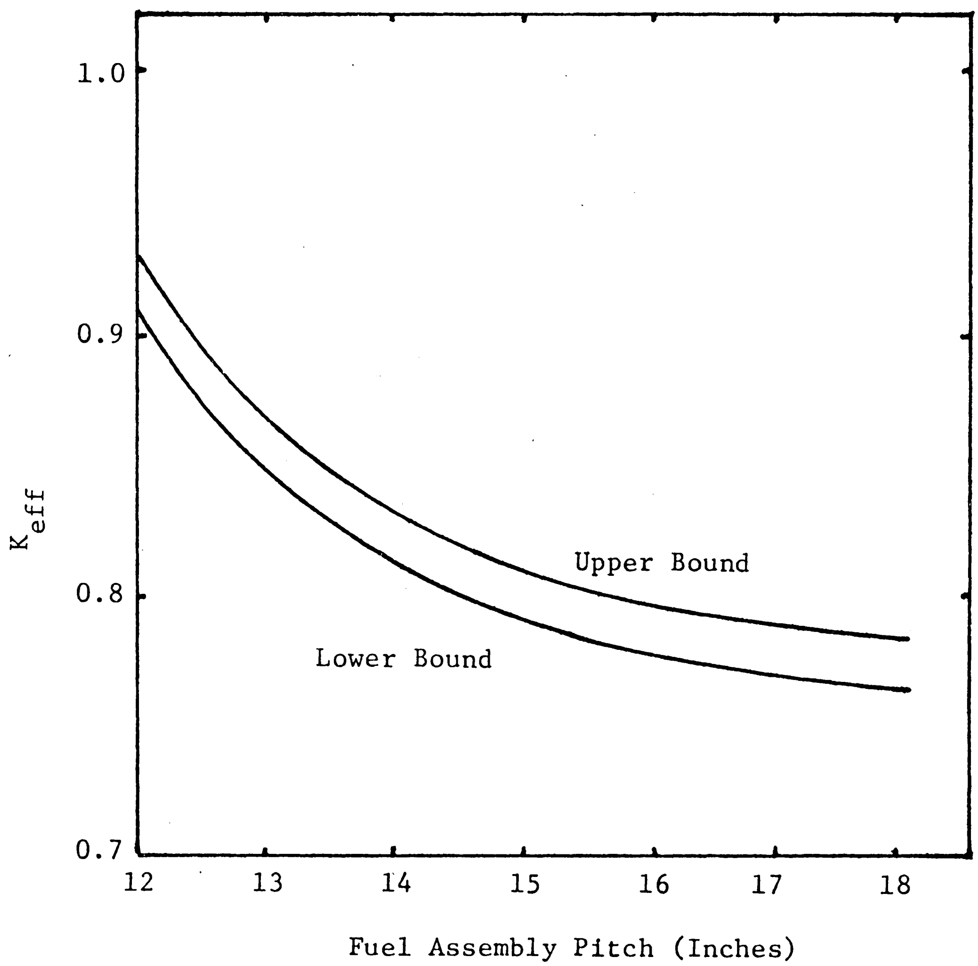


Figure 3.2. Typical Evaluation of K_{eff} for a New Fuel Storage Arrangement.

The present halt in spent-fuel reprocessing has motivated a number of manufacturers to market redesigned spent-fuel racks to accommodate more assemblies in a typical reactor pool.

Combustion Engineering Company[12] is offering fuel racks with reduced spacing, where each assembly is enclosed in a stainless steel cell. In general, new racks may accommodate one core and one to six annual reloads depending upon the design of the existing facility. This increases storage time to five years.

Nuclear Services Corporation (NSC), Cambell, Calif.,[8] has developed a plan to increase the storage capacity of typical spent fuel reactor racks through reconfiguration and/or by providing additional neutron absorbing shielding. Without the shielding, the spacing between PWR fuel peaks can be reduced through reconfiguration from typical 20 to 14 inches. This provides capacity for an additional four years by doubling the existing capacity of the pool. The company reports that with the use of neutron absorbing-shields, PWR pool capacities can be tripled, effectively increasing the storage time to five to eight years.

Nuclear Utility Services (NUS) Corp., Rockville, Md.[12] designed a rack for PWR assemblies with a reduced center spacing of 10 1/2 inches. In this design seven boron carbide pins are placed at the four sides of the assemblies. This arrangement, it is claimed, permits eight to ten years of storage capacity. For BWR pools, NUS has developed a rack with Boral plate casings. This rack allows an extended storage capability for eight to ten additional years.

Costs of new high-density spent-fuel racks are currently commercially sensitive, but some estimate of their range can be made. The price of the structural material needed to encase one typical LWR element, one cell, may range from about $1,300 to $3,000.[45] New high-density rack installation costs including decontamination of the old racks may average about $1,000 per MT[45] rendering the total cost of new rack material and installation costs in the range from $4,000 to $7,500 per metric tonne of fuel. For example, total costs associated with the expansion of a 1,000 MWe LWR fuel basin by 150% to a 500 MT capacity may average $3 million in 1976 dollars. Storage costs for spent fuel placed in the reactor pool are part of the operation and maintenance expenses.

Since it is very difficult to perform installation work in a basin where spent fuel is already stored, careful planning must precede the installation. The need to transport and store spent fuel off-site may involve in a tight storage situation a time consuming and costly effort. This is because, in addition to decontamination of the old fuel racks, repeated decontamination of the spent-fuel transportation cask is required. Therefore, the most convenient way to acquire an additional spent-fuel storage capacity is to modify spent fuel storage basin of new reactors coming on line. If a change of physical dimensions cannot be executed, the next best activity is to install new expanded racks before the first spent fuel is discharged. Assuming that the basin capacity of a new reactor is 140% of a full core load, the additional capacity in excess of full core reserve can be expressed as

$$\Delta C = (1.4\ M - 1) \quad FCR, \tag{3.1}$$

where

FCR = full core reserve of the reactor

M = multiplier expressing the technological feasibility of the spent-fuel rack expansion under the constraints of maintenance of subcriticality of the storage pool and capacity of the pool.

The maximum addition of spent-fuel racks in a time period can be expressed by the formula

$$L_{1k} = \Delta R_k (1.4\ M - 1)\ FCR\ , \tag{3.2}$$

where

ΔR_k = number of reactors installed in period k, and

L_{1k} = upper limit on spent-fuel storage capacity addition in period k by installing expanded racks in new reactors coming on line.

It is expected that the technological limit on the on-site storage capacity expansion, expressed by factor M, will have a significant influence on the storage capacity expansion program.

The existence of storage capability associated with new power plants brought on line can provide interim storage for spent fuel which has to be removed from a reactor with a partially filled basin in order to perform installation of new racks. In this sense, the upper-limit on on-site storage expansion can be somewhat relaxed. It is obvious that this provision would involve additional transportation expenses unless the new reactor is installed on the same site. The initiation of spent fuel reprocessing and/or disposal relax requirements on spent-fuel storage. Removal of spent fuel from the reactor basin for reprocessing may facilitate plans for capacity expansion of the existing basins and thus lead also to relaxing of the upper limit on on-site capacity expansion.

3.4.2 Off-Reactor-Site Spent-Fuel Storage

As an alternative to spent-fuel storage at each reactor site, the possibility of storing spent fuel away from the reactor has been considered.[5] Such storage could be accommodated either in spent fuel pools associated with the reprocessing plants or in some central independent storage facilities. Because of relatively high transportation costs, which will be discussed in Section 3.5, it seems that a few central facilities would be an economic optimum, in order to balance transportation costs against capital expenditures incurred by such facilities. These facilities could be located either near the reprocessing plants or on federal reservations. It is expected that central independent pools would be built on a modular basis with additional capacities added every few years to provide storage for discharged fuel assemblies.[22]

Some scoping economic calculations have been performed on a central storage facility of several thousands tonne capacity.[4]

Such facilities are costly. They must be built to adhere to seismic and tornado safety standards. They must include cask loading and unloading equipment, decontamination facilities, water chemistry laboratories, radioactive waste systems, and radiation monitoring systems.(40)

A large storage facility would require three to four years to design, construct,and put into operation. It was found that costs depend on financing assumptions, (mode of financial participation of the interested utilities), the period of utilization of the facility, and the assumptions about the pattern of loading of spent fuel at the start of its life. It was found that the cost of independent storage pools of several thousand tonnes of storage capacity would be in the range from $15,000 to $25,000 per MT of spent fuel.(32) E. R. Johnson Associates, Inc. have proposed an independent spent-fuel pool project of 1,000 MT capacity which is equivalent to a capacity of 2250 PWR or 4500 BWR assemblies. The estimated capital investment is $20,000,000, i.e., a unit cost of $20,000 per MT of stored fuel.(46)

An alternative to construction of independent storage pools is to expand storage facilities at the reprocessing plants. The common design capacity of reprocessing plant storage pools is for the handling of a three to four month throughput. For a 1500 MT/year reprocessing plant, the storage pool capacity is about 500 MT of fuel.(32) An expansion of these facilities to capacities above the optimal four month throughput would require additional costs which would have to be borne by the users of the storage service in terms of increased annual spent-fuel storage costs.

There are certain advantages in the association of an independent pool with the reprocessing plant. In view of reprocessing as the ultimate disposition of spent fuel, an economy of scale can be achieved in using the independent pool bath as as a spent-fuel receiving and as a interim waste storage area. Another advantage is the avoidance of double handling costs and double shipping charge which would be carried if an independent storage pool service is used. Installation of an independent storage pool, the most costly of the spent-fuel storage alternatives, may be justified if planning of the next needed reprocessing capacity installation would be deferred for several years and/or if deferral of plutonium recycle would occur for an indefinite period because of licensing, political, or economic constraints.[32]

The annual holding costs for spent-fuel storage are expected to range from $5,500 per metric tonne per year for a utility owned storage facility[35] to $20,000 per metric tonne-year for a commercial facility.[47] A figure of $7,000 per MT of fuel can be assumed typical for facilities where utilities supply some form of long-term commitment or some front end money.[4] The variation of these costs over time may be estimated using an appropriate escalation factor related to a variation in labor costs.

The report, ERDA-25, Edition 1976, contains a survey of off-site storage facilities available in January 1976 and announced expansions of these facilities in the future. These off-site storage facilities are associated with the reprocessing plants. Among currently available off-site storage facilities are the spent-fuel basin of the GE Morris facility with 700 MTU of storage capacity and Nuclear Fuel Services West Valley plant with 250 MTU storage capacity. On January 1, 1976, 257 MTU of the total capacity of those basins was filled with spent fuel and 693 MTU of capacity remained unused. In view of the expected shortage of spent fuel storage capacity, NFS planned to expand its storage basin by 45 MTU in 1976 and AGNS announced that it would have its basin of 360 MTU capacity ready in 1977.[5]

3.5 Spent Fuel Transportation

After discharge from the reactor, the spent fuel is usually cooled in a fuel storage pool for a minimum of four to five months. Spent fuel generates large amounts of heat through the radioactive decay of materials contained in the spent fuel. These materials are activated structural material, transuranic elements, and radioactive fission products. Spent fuel shipping casks therefore have to provide adequate radiation shielding and heat removal capacity during transportation. Also, the arrangement of spent-fuel elements in the transportation cask must be such as to prevent formation of a critical mass.

The physical and radiological characteristics of spent fuel, combined with the constraints imposed by Federal Transportation regulations, place stringent requirements upon spent-fuel transportation.

Spent fuel assemblies from PWR's are 22 x 22 x 400 cm arrays of 264 Zircaloy fuel pins each of which is about 1 cm in diameter. The assembly weighs about 670 Kg. BWR assemblies are smaller forming 14 x 14 x 450 cm long arrays consisting of Zircaloy pins of 1.4 cm in diameter. This assembly weighs about 280 Kg. The activity of a typical spent fuel element is about 1.8×10^6 Ci.(14) There is also a significant neutron flux produced from the spontaneous fission of Cm-242 and Cm-244 contained in the spent fuel. The strength of this source is about 1.3×10^9 neutrons/sec.(14) The characteristics of the typical LWR spent fuel after 120 days of cooling time are summarized in Table 3.9.

The heat of about 8.4 KW, which is generated in the spent-fuel assembly, has to be removed during transportation in order to prevent thermal damage of the spent-fuel package and to remain below maximum temperatures specified in Federal regulations. Shielding, heat removal, and subcriticality requirements make spent-fuel shipping casks physically very large. The containers are from about 20 to 30 times heavier than the fuel. This fact limits the number of spent fuel assemblies that can be shipped by truck or railroad car.

Spent-fuel shipping casks in use today are designed for spent fuel with characteristics corresponding to a minimum cooling period of four months. Shorter cooling times would lead to greater requirements for shielding protection and for cooling, resulting in heavier and more expensive casks. Casks are available for both truck and

Table 3.9. Characteristics of Spent Fuel.[14]

Assembly total weight [Kg]	454
Uranium/assembly [Kg]	311
Total radioactivity [Ci]	1.9×10^6
Fission product activity [Ci]	1.7×10^6
Transuranic content [Kg]	5.5
Transuranic activity [Ci]	$1.5 * 10^5$
Neutron source strength [n/cm^3-sec]	1.3×10^9
Total thermal power [KW]	8.4
Total gamma power [KW]	1.4
Exposure [MWD/MTU]	25000
Average specific power [MW/MTU]	35

railroad transport. Data describing the shipping casks currently available for LWR generated spent fuel are summarized in Table 3.10.

A shipping cask for railroad transportation, which is currently being used, is the cask IF-300. It is a water cooled cylindrical cask designed to carry 7 BWR or 18 BWR fuel assemblies. Shielding is provided by water filling which also serves as a cooling medium and by 10.2 cm of depleted uranium metal in the cask shell. Heat is removed by natural circulation from the fuel and transmitted through the cask sides and ends by conduction. The corrugated cask packet is cooled by two diesel-motor driven blowers with a total air moving capacity of 8.5 m^3/sec. The heat generated from 7 PWR assemblies with a burn-up of 35,000 MWd/MTU at an average specific power of 40 MW/MTU after 120 days cooling is about 77 KW. The cask is normally transported by rail on a 100 tonne capacity flat car. It may also be transported on highways by special nine wheel overweight trucks.

The spent fuel cask, TN-8, is cylindrical and uses a "dry" cooling method. The inner cavity of the cask is divided into three compartments each of which is able to contain one PWR assembly with maximum burn-up of about 38,500 MWd/MTU and a minimum cooling time of five months. Shielding is provided by lead. Neutron shielding consists of 150 mm of resin affixed to the outer surface of the outer cask shell. A large number of nickel coated fins welded into the outer cask shell, and passing through the neutron shield resin layer, provide a means of dissipating the generated heat into the ambient air. The maximum heat load is 35.5 KW. The cask weighs about 36 MT and

Table 3.10. Spent-Fuel Shipping Casks.[14]

Common Name	# Assemblies PWR/BWR	Shielding	Heat Capacity [KW]	Loaded Cask Weight [MT]	Transport Mode	Available Current/ Under Constr.
NFS-4	1/2	lead	11.5	24	truck	6/0
NFS-5	2/4	uranium	20	25	truck	0/0
IF-300	7/18	uranium	76	74	rail	4/0
TN-8	3/0	lead	35.5	36	overweight truck	0/2
TN-9	0/7	lead	24.5	36	overweight truck	0/3
TN-12	12/32	steel	~ 95	97	rail	0/1
NLI-1/2	1/2	lead	10.6	22	truck	3/2
NLI-10/24	10/24	lead	100	88	rail	0/12
BCL-6	1/1	lead	12.0	22	truck	0/1

overweight transportation permits are required. TN-9 is a similar cask designed for carrying seven BWR assemblies with maximum heat removal capacity of about 24.4 KW, which corresponds to the heat output of seven BWR assemblies with a maximum burn-up of 36,500 MWd/MTU cooled for at least five months.

Expenditures related to spent-fuel transport consist of charges for transportation itself, cask leasing, amortization of the cask investment, and nuclear insurance. Spent-fuel transportation costs depend on the outcome of rate determination actions currently in progress. It was stated that unprecedented and unwarranted demands are being made by the railroads for special train service with reduced speeds for both loaded and empty casks.[20] It has been estimated that for a typical reactor 500 miles from a reprocessing plant, the regular round trip freight costs would run about $2500 per tonne of fuel (i.e., $5/MT-mile).[4] If special trains are required on the loaded shipment, this cost increases to about $5,500 per tonne ($11/MT-mile).[4] The requirement of special trains both ways, would result in an increase to about $8,500 per ton (i.e., $17/MT-mile).[4] When the lease cost of a multi-element rail cask is included in freight figures, the overall transportation cost, exclusive of loading and unloading costs, would be in the range of $12,000 to $18,000 per ton of fuel, i.e., from $24 to $36 per ton per mile.[4] An estimate of variation of railroad shipping costs over time was made by Larkin.[35] This estimate is presented in Table 3.11.

Table 3.11. Railroad Shipping

Cost Projections

Year	1975	1980	1985	1990	1995	2000
Cost [$/MT-mile]	37.0	37.5	38.0	39.5	41.0	47.0

Transportation costs by truck were estimated to be on the average \$20/MT.[48] Handling costs related to loading and unloading the spent-fuel transportation cask were estimated to range from \$4 to \$5 per MT per mile.[44]

4. SPENT-FUEL VALUE

An important part of the spent-nuclear-fuel picture is the spent-fuel value. Spent fuel may be considered as a "mineral" which can be "mined" (reprocessed) to recover the unused nuclear fuel. Hence, spent fuel value depends upon the balance between the market values of the recovered products and the "production" (reprocessing) cost.

This chapter contains a detailed examination of the spent-fuel value which is a composite value of the both recovered products: uranium and plutonium. Since plutonium value is determined by the mode in which plutonium is used, both plutonium recycle in the light-water reactors and in the fast breeders is discussed. Also a review of the mixed-oxide fuel fabrication and plutonium storage is presented here.

The spent-fuel value analysis complements the examination of the spent-fuel storage problem that was presented in Chapter 3. Spent-fuel revenues are important parameters of the spent-fuel storage model developed in Chapter 5.

4.1 Uranium Value of Spent Fuel

The uranium recovered in the reprocessing facility can be recycled back into the nuclear fuel feed stream. Since the fissile uranium assay (U-235) in the spent fuel discharged from LWR's operating under equilibrium conditions is higher than that of natural uranium, spent fuel can provide a savings in requirements for natural uranium feed and separative work.

Enrichment expenses in a gaseous diffusion plant are proportional to separative work, the cost of which reflects the energy consumption needed to produce enriched uranium. An analysis of a gaseous diffusion cascade[49,50] provides a value for enriched uranium product, the cost of separative work, and waste stream composition. The detailed drivation of a relationship expressing the value of enriched uranium product is presented in Appendix 2. Here, the final result is stated as

$$D = C_s[V(x_p) - V(x_w) + \frac{x_p - x_w}{x_f - x_w} (V(x_w) - V(x_f))],$$

where

$$V(x) = (2x - 1) \ln \frac{x}{1 - x} , \quad \text{and} \qquad (4.1)$$

where

D = price of the enriched product, \$/Kg

C_s = unit cost of separative work, \$/Kg

C_f = unit cost of uranium feed, \$/Kg

x_p = assay of uranium-235 in the enriched product, weight fraction

x_f = uranium-235 assay of the feed uranium, weight fraction

x_w = diffusion plant tails assay, weight fraction.

The dollar value of the enriched product, and also of recovered uranium, is sensitive to the assumptions made with respect to unit prices of uranium feed and separative work over time.

For the typical spent-fuel isotopic characteristics shown in Table 4.1, a savings associated with reusing recovered uranium can be calculated.

The calculation of the recovered uranium value from the reference LWR spent fuel (see Table 4.1) in terms of natural uranium feed and separative work costs were carried out on the basis of the enrichment plant tails assay being 0.25%. By substituting the data into the equation for D, (4.1), the value of recovered uranium is given by

$$D = C_s \times 0.15 + C_f \times 1.32 - C_c, \qquad (4.2)$$

where C_c represents the unit cost of conversion of uranium to UF_6 gas.

This result indicates that one unit of recovered uranium from the reference LWR spent fuel can serve to reduce the requirement for natural uranium by 1.32 units and for separative work by 0.15 units. The formula (4.2), corrected for losses during reprocessing and fabrication, can be written as

$$D = (C_s \times 0.15 + C_f \times 1.32 - C_c)(1 - \eta_1 - \eta_2), \qquad (4.3)$$

where

η_1 = loss during reprocessing (~ 0.005)[22]

η_2 = loss during fabrication (~ 0.003).[22]

Table 4.1. Characteristic Spent-Fuel Discharge Data.[16]

Type of plant (1,000 MWe)	PWR	BWR	Reference LWR
Amount of discharged fuel (MT)	29	35	32.69
Amount of U235 in recovered U [Kg]	248	272	252.44
U235 assay (%)	0.891	0.81	.861
Amount of Pu239 and Pu241 [Kg]	194	232	204.00

Note: Reference LWR is a hypothetical light-water reactor corresponding to the mix of BWR to PWR given by ratio of 1 to 2.

It was shown that the values of recovered uranium from spent fuel are related to prices of uranium (U_3O_8) and of separative work. Uranium is relatively scarce and competition is intense for the uranium that is available.[51] The formation of an uranium market and consequently of the price of uranium depends upon the balance between demand and supply. Supply and demand in the future market will be influenced by many factors. Among the most important ones are: electric power generation growth, additions to domestic reserves, uranium production costs, existence of plutonium recycle, and the growth of international trade in uranium. It is estimated that future prices of uranium will continue to rise between 1976 and 1980 because of heavy demand on limited uranium production capacity and higher costs to develop needed reserves. The odds are equal that plutonium recycling will or will not be implemented.[51] However, it is estimated that plutonium recycle will have little effect in reducing uranium demand pressures.[51] The expectations are that after 1980 the rate of uranium price increase will be reduced as more reserves are proven and as international trade in uranium expands.[51] It was forecasted that the present U_3O_8 price of \$35.0 per Kg will reach a level of \$83.8 in 1980 and then at a reduced rate of increase will approach \$101.4 will occur in 1985.[51] For the purpose of this study, it is assumed that the rate of U_3O_8 cost increase prevalent in the period 1980-1985 will continue to the end of this century. The forecasts of future uranium prices are summarized in Table 4.2.

Table 4.2. Uranium Price Forecast.[51]

Year	1976	1980	1985	1990	1995	2000
Price U_3O_8 [$/Kg]	35.0	83.8	101.4	130.0	157.0	186.0

In the U.S. today, the only supplier of enrichment is ERDA's diffusion plant complex. Since the diffusion enrichment process is energy intensive, a sharp increase in the cost of this service from \$26 per Kg of separative work in 1971 to \$44.25 in 1975 was experienced. The enrichment service price in the current year (1976) has reached \$60 per Kg SWU. It is expected that further price increases are imminent due to spiraling power costs.[52] The current consensus of technical and economic experts is that new enrichment facilities should use the centrifuge process, because of the diffusion plant's intensive capital requirements. Long lead times are involved in bringing both the enrichment plant and the electric power support system into operation, thus compounding the problem of obtaining the required capital. Another factor in favor of the centrifuge plant is that about 90% of the electric power supplied to the diffusion plant is dissipated in the form of heat.

The plant capital investment for the centrifuge is of the same order as for the diffusion plant (\$1.5 to \$3.0 billion for rating of about 9 million SWU per year.[52] The centrifuge has relatively small power requirements. It can be adapted to modular construction and offers a greater potential for technological improvements. It is expected that new enrichment plants will be brought on line in 1983. Estimates of future costs of enrichment services are summarized in Table 4.3.[52] Table 4.4 presents the forecast of uranium conversion (to UF_6 cas) costs.[35]

Table 4.3. SWU Price Forecast.[52]

Year	1976	1980	1985	1990	1995	2000
SWU [$/Kg]	60.0	111.0	165.0	159.0	153.0	147.0

Table 4.4. Uranium Conversion Cost Forecast.[35]

Year	1976	1980	1985	1990	1995	2000
Conversion cost[$Kg]	3.5	3.8	4.4	5.1	5.7	6.6

4.2 Plutonium Value

Plutonium value is determined by the manner in which plutonium is used. One must distinguish here between plutonium price and plutonium value. The value is to be understood as a "use value", which is the sum of money one is prepared to pay to use a commodity. A market price depends upon the balance between supply and demand. Considering the current standstill of reprocessing capability in the U.S. with consequent unavailability of plutonium, a market price for plutonium is nonexistent.

To define the use value (limiting value for plutonium in the plutonium market), it is necessary to know precisely the technical and economical circumstances of its utilization.(53) Since plutonium, if recycled, can replace U-235, the plutonium market is obviously linked with uranium and enrichment services markets.

Plutonium generated in LWR's can be used in situ (there is no need to handle plutonium within the reactor), for recycle, for the High Temperature Gas Reactor (HTGR) using a plutonium fuel design, and for the early fuelings of the fast breeders.

4.2.1 Plutonium Consumption In Situ

Fissile plutonium, which is formed in the reactor core, participates in the general fission reaction at the same time as U-235. The more fissile plutonium, Pu-239 and Pu-241, that is formed in the reactor, the more important is the in-situ consumption. The energy share produced by the fission of plutonium varies with the neutronic characteristics of the reactor and the degree of burn-up. A typical LWR core which uses enriched uranium dioxide (UO_2) fuel rods near the end of the equilibrium cycle, at an average core exposure of 20,000 MWD/MTU, will derive approximately 50% of its power from the fissioning of bred-in fissile plutonium isotopes.[54] No value can be assigned to this plutonium since it is freely available and no payment has to be made.

4.2.2 Pu Recycle in LWRs

Plutonium remaining in the spent fuel (after its formation and partial destruction in the reactor) can be chemically separated (reprocessed) from the uranium and fission products contained in the spent fuel. It can be reintroduced into the same reactor, associated either with natural, enriched or depleted uranium (e.g., diffusion plant tails).[54] The effect of this recycled plutonium in the reactor will depend upon its characteristics (composition of Pu fissile and Pu fertile (Pu-240, Pu-242)); (i.e., upon the conditions of its formation because its isotopic composition varies with burn-up of the core where it was formed). During the next decade there will be a transition from 1976, when the majority of the fuel will be discharged at low exposures, to a situation in 1985, where the fuel will be predominantly at equilibrium exposures.[37] The average composition of plutonium available for recycle is shown in Table 4.5 where the projected discharges from the PWRs and BWRs are mixed on a

Table 4.5. Average Composition of Plutonium Available For Recycle.[37]

Year	Plutonium Composition (wt %)					
	Pu 236	Pu 238	Pu 239	Pu 240	Pu 241	Pu 242
1975	0.006	1.0	64	22	10	3
1980	0.007	1.5	58	24	11	5
1985	0.007	1.7	54	25	12	7

year-by-year basis. The numbers presented in Table 4.5 are useful for determining the average value of plutonium in the time periods in which it can be expected that the reprocessing plants will be operational; thus, allowing plutonium recycle on an extensive scale in the LWRs.

When plutonium produced in a light water reactor is recovered, recombined with uranium, fabricated into fuel rods (mixed-oxide (PuO_2 - UO_2) fuel rods), and reinserted into the same LWR core displacing an equipment number of U-235 enriched rods, the resulting reactor can be described as a "self-generation-reactor" (SGR). The SGR recycles all plutonium: fissile and non-fissile plutonium isotopes. The SGR concept of operation, or its near equivalent, is expected to constitute the industry-wide form.[22] The maximum excess plutonium loading above the self-generated quantity, currently not expected to constitute an unjustifiable extension to present UO_2 reactor technology, is 15%. This type of reactor is referred to as a 1.15 SGR. In this type of reactor one-third of the fuel rods are mixed-oxide; the remaining ones are the enriched UO_2 fuel rods.
An LWR is judged to be equivalent to an equilibrium 1.15 SGR when the weight ratio of total Pu to total fissile nuclides in the charged fuel is not greater than 0.65; i.e., for

$$\frac{Pu_f + Pu_{nf}}{Pu_f + U_f} < 0.65 \tag{4.4}$$

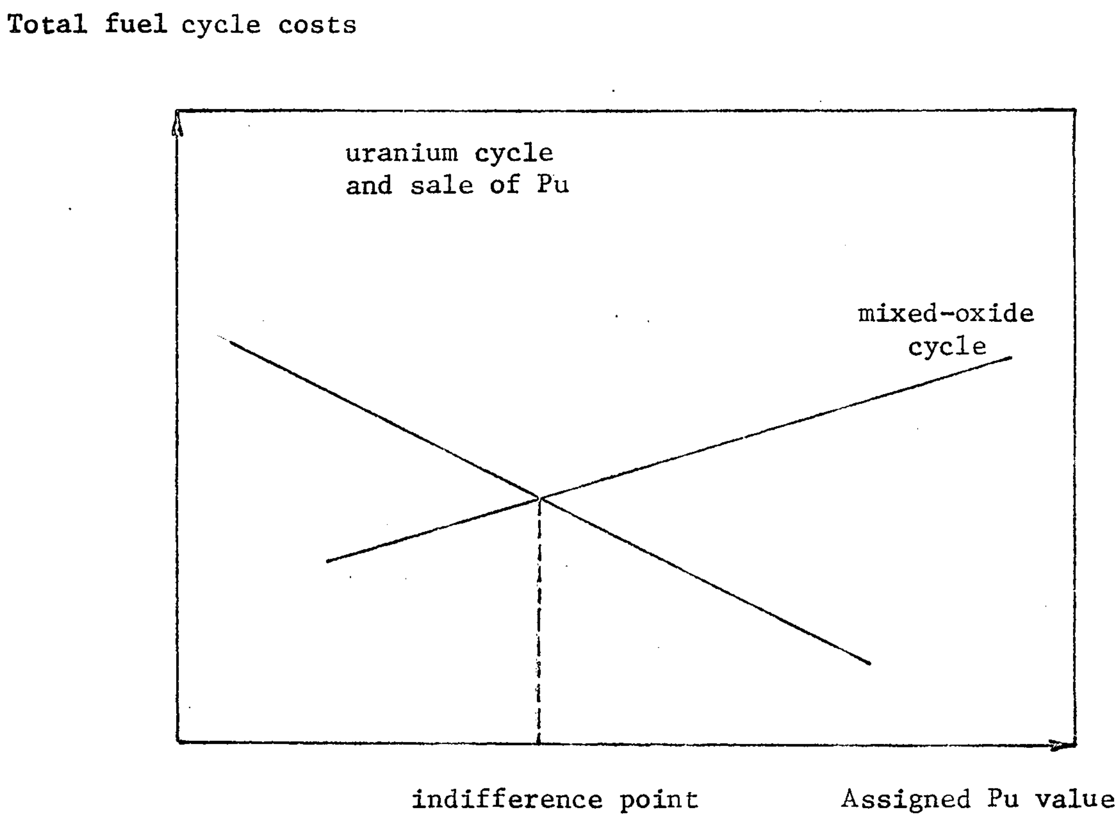
where

Pu_f = Pu-239 + Pu-241

Pu_{nf} = Pu-240 + Pu-242

U_f = U-235

For the purpose of this study the plutonium value will be that derived from the recycling of plutonium in LWR's (1.15 SGR). The value of plutonium can be determined in several different ways. The method used most frequently in economic analysis of fuel cycle costs is the so-called indifference, or break-even method of plutonium valuation proposed by Eschbach.(55) The indifference method defines Pu value as the value yielding the same fuel cycle costs whether the plutonium discharged is sold or recycled. In this method, numerical values for each fuel cycle component for both enriched uranium fuel and plutonium recycle fuel must be established, leaving only the price of plutonium as an unknown. A high value of plutonium will give the uranium-235 enriched cycle a low fuel cost; but, in a non-breeding reactor, it will give the plutonium oxide cycle a high fuel cost. If the fuel cost is considered to be a function of plutonium price, the fuel cost of the enriched uranium cycle with plutonium sale and the fuel cycle costs of the mixed oxide cycle will be represented by two lines, see Figure 4.1. The intersection of the two lines determines the "indifference" point since the fuel costs are the same for both cycles. Obtaining fuel cycle costs for the plutonium value analysis is different since calculations involve many parameters, particularly when considering the different modes of recycle and core loading strategies.(56,57)



(corresponding assigned plutonium price

defined as plutonium value)

Figure 4.1 Plutonium Value Indifference Curve.

Another way to determine plutonium value is to calculate its "basic" value. The basic (intrinsic) value of plutonium is derived from the initial fuel content in plutonium recycle fuel which is capable of the same exposure as uranium fuel. Eschbach has shown that for the most of practical purposes the value of plutonium is directly proportional to the price of fully enriched uranium (~ 93% U-235) in the AEC Price Schedule.(56) This concept accounts for corrections in the value of plutonium for changes in separative work and uranium prices.

Deonigi derived a generalized plutonium value equation which includes a relationship with fully enriched uranium, the plutonium-242 penalty factor and the differential fabrication cost correction for mixed-oxide fuel above that of uranium fuel.(37) It was shown that

$$\text{Plutonium value} = AxU - 0.16xP - \frac{\text{incremental fabr. cost/Kg fuel}}{\text{gram fissile plutonium/Kg fuel}}, \quad (4.5)$$

where

A = relative worth of plutonium-239 to U-235 as fissile material

U = cost of fully enriched uranium (93% wt)

P = ratio of concentration of plutonium-242 to the concentration of fissile plutonium expressed in per cent.

The fabrication charge for the mixed-oxide assemblies can be determined by using the fabrication penalty B (%) in the following relation:(57)

$$F_{Pu} = F_u[0.32 + 0.68(B + 100)/100] , \qquad (4.6)$$

where F_{Pu} and F_u are the fabrication costs of plutonium and uranium fuel assemblies, respectively.

The use of the plutonium indifference value does not appear to be useful in the present situation of a non-existent plutonium market brought on by regulatory circumstances and non-existance of reprocessing capability. It appears realistic, that for an economic analysis of spent fuel storage, one should consider the plutonium value to be equal to savings realized by reduction of uranium ore and separative work needs at the time when the recycle permitted.

In the GESMO study,[22] an estimate of the savings in uranium ore and separative work needs realized by plutonium recycle was evaluated on the basis of present offerings of major fuel suppliers. It was found that one gram of fissile plutonium in a PWR is equivalent to 0.1906 Kgs of separative work plus 0.180 Kgs of natural uranium. A similar analysis for BWR fuel cycle plants indicated that one gram of fissile plutonium in a BWR is equivalent to 0.2037 Kg's of separative work plus 0.1870 Kgs of natural uranium. Obviously, the corresponding savings in terms of costs will change with time, depending on the price that must be paid for natural uranium and separative work at the time when plutonium recycle actually takes place. The actual value of a gram of plutonium produced must take into account reprocessing and fabrication process material losses, decay of plutonium-241 during the storage of spent fuel, reprocessing and fabrication, and also the cost difference between mixed-oxide fabrication and uranium fuel fabrication. Reasonable losses are 0.5% during reprocessing and 0.3% during fabrication.(22) Plutonium-241 decay over the reprocessing-fabrication time span may account for further loss of about 1% in fissile plutonium.(22)

Plutonium value is summarized in the following formula:

$$V = (C_s \times a + C_f \times b)(1 - \eta_1 - \eta_2 - \eta_3) - \frac{\Delta FC}{g} , \qquad (4.7)$$

where

V = plutonium value, \$/g

C_s = separative work unit price, \$ per Kg

C_f = natural uranium feed cost, \$ per Kg

η_1 = loss during reprocessing (~ 0.005)(22)

η_2 = loss during fabrication (~ 0.003)(22)

g = number of grams of Pu fissile per Kg of mixed-oxide fuel

η_3 = loss of fissile plutonium blue to decay of Pu-241 during fabrication and reprocessing ($\simeq$ 0.01).

The factors a, (equivalent of one gram of fissile plutonium in terms of separative work units, Kg), and b, (equivalent of one g of Pu_f in terms of natural uranium, Kg), which vary with the type of reactor, are summarized in Table 4.6.

Table 4.6. Plutonium Value Uranium Feed and Separative Work Equivalents.[22]

Equivalents of 1 g of Pu_f	Type of reactor	
	PWR	BWR
a, SWU equivalent of 1 g Pu_f, Kg	0.1906	0.2037
b, Nat. U equivalent of 1 g Pu_f, Kg	0.1800	0.1870

4.2.3 Plutonium Use in the Fast Breeders

One of the possible final uses of plutonium is its use as the initial loading of fast breeder reactors. Since the commercial breeders are not expected to come on line before the early 1990's, the plutonium recovered through reprocessing may have to be stockpiled before its use as a fast breeder fuel. The length of plutonium storage will have an effect upon the economics of plutonium because of cost accrual due to storage and the depletion of fissile plutonium-241 through decay.

It was estimated that annual storage costs may run from $1 to $2 per gram of fissile plutonium.(22) The value of plutonium in fast breeders is rather difficult to estimate. The "indifference method" does not appear suitable for this determination because neutronic characteristics of the fast breeder compared with LWR are vastly different. Among the principal characteristics of the fast breeder are reduced fissile inventory and the existence of a breeding ratio greater than one. However, the plutonium value is related to the price of fully enriched uranium.(55) Some authors have estimated that the value of plutonium in the fast breeder may be 100% to 200% greater than the price of fully enriched uranium.(22,57) A detailed economic analysis of the LWR produced plutonium in the fast breeders is beyond the scope of this study. However, the impact of revenues associated with plutonium use in fast breeders on the overall spent fuel storage economics may be assessed.

4.3 Mixed-Oxide Fuel Fabrication

Recycle of plutonium in LWR's requires production of mixed uranium dioxide-plutonium dioxide fuel (MO_2). Mixed-oxide fuel may be used to form separate fuel assemblies of mixed-oxide fuel (PWR concept), or used as islands of the mixed-oxide fuel surrounded by enriched uranium rods in a single assembly (BWR concept).[54]

The fabrication process for mixed-oxide fuel is known, but has not been demonstrated on a commercial scale. The delays in design and construction of mixed-oxide fuel fabrication facilities are related to the problems generated by current government regulatory policies concerning large scale plutonium recycle. Among the uncertainties pertinent to the design of mixed-oxide fuel fabrication facilities, the major impact results from the co-location of reprocessing and fabrication plants and plutonium safeguards issues. Indeed, the plutonium issue has had the greatest impact upon the mixed-oxide fuel manufacturers. An interesting point here is that apart from all other factors which are beyond control of a MO_2-fuel manufacturer, he faces the risk of having no real market for mixed-oxide fuel while at the same time making a substantial investment for this purpose.[32] The MO_2 fuel fabrication facility lead time is about seven to nine years including financial arrangements, design, licensing, and construction.[4] Currently, only one project, the Westinghouse plutonium fuel fabrication plant, planned for Anderson, S.C., is being implemented. It is assumed that the Westinghouse plant may start up in late 1981 with an 150 MT throughput in 1982, and reaching a full nominal yearly output of 300 MT in 1983.[32] Plutonium recycle issues together with limited mixed-oxide fuel fabrication experience make estimates of the actual costs of MO_2 fuel fabrication very difficult to determine. There is limited experience on which to base mixed-oxide fuel fabrication cost projections, even if the regulatory requirements were known exactly.[32] An attempt was made to arrive at a roughly estimated price for mixed-oxide fuel fabrication and related activities.[58] It was estimated that the trends toward the end of this decade would be about $250 per Kg of MO_2 fuel compared to $130 (with inflation excluded about $100) per Kg of uranium enriched fuel.[58] Additionally the plutonium nitrate ($Pu(NO_3)_4$)-to-oxide (PuO_2) conversion cost is in the range of $1 to $2 per g of fissile plutonium.[58] Since each Kg of the MO_2 fuel is expected to contain plutonium in the range of 35 to 40 gms,[37,58] the conversion adds about $60/Kg to the cost of mixed-oxide fuel. With safeguards and waste management treatment charges, the estimate totals approximately $330 per Kg of MO_2 fuel.[58] In the study by Larkin,[35] an estimate of uranium and mixed-oxide fuel fabrication costs up to the year 2000 was made. The data on MO_2 fuel fabrication cost in that study were corrected by about 25% to include safeguards and waste management costs. The mixed-oxide fuel versus uranium oxide differential costs forecast are summarized in Table 4.7.

Table 4.7. Fuel Fabrication Costs Forecast.[35]

Year	Fuel fabrication costs [\$/Kg]		Cost differential [\$/g of Pu_f]
	UO_2	MO_2	(*)
1976	199.7	306.25	4.67
1980	130.00	330.00	5.00
1985	148.8	378.4	5.74
1990	169.34	430.48	6.52
1995	189.87	482.6	7.32
2000	208.68	529.7	8.03

Note: *Fuel fabrication cost differential of mixed oxide versus uranium oxide was related to the content of 40 g of fissile plutonium per Kg of mixed oxide fuel.

4.4 Plutonium Storage

In the case in which a longer term temporary ban on plutonium recycle in LWR's was imposed or if there were an incentive to stockpile plutonium for later use in fast breeder reactors and only uranium were recovered through reprocessing and recycled, a need for longer term plutonium storage would arise. Plutonium storage needs also may arise because of the lack of mixed-oxide fuel fabrication capability. The rate of generation of plutonium backlog is given by differences in the rate of reprocessing and the mixed-oxide fuel fabrication rate. In their paper presented at the AIF Fuel Cycle Conference, B. Wolfe and R. Lambert[4] pointed out a need for adequate mixed-oxide fuel fabrication capability required to keep pace with the plutonium production over time. It was estimated that under the present trends of nuclear power growth and planned reprocessing capacity start-up in about 1980, there would be a need for about one thousand tonnes per year of mixed-oxide fabrication capacity, and by 1990 about 1600 tonnes per year of capacity in order to produce mixed-oxide fuel from the plutonium in the discharged fuel. The GESMO study[22] indicated that in the next two decades there may be sufficient plutonium storage capacity at the planned reprocessing and fabrication sites to store the plutonium, if plutonium is recycled in LWR's. However, under the scenario of insufficient mixed-oxide fabrication capability or incentive to stockpile plutonium for breeder use,this situation might change. A rough estimate of plutonium storage capacity needs in the absence of plutonium recycle in LWR's indicated that about 300 MT of fissile plutonium would have to be stored by 1990 while only 35 MT would have to be stored if plutonium were recycled.[22] This situation is approximately equivalent to plutonium storage needs if plutonium were stockpiled for use in the commercial fast breeders. It was estimated that a 300 MT fissile plutonium single structure facility would cost $60,000,000 with annual operation costs of about $1,000,000. These costs would be reflected in approximately $1 to $2 per g of fissile plutonium storage costs per year.[22,37,57] Economic considerations about such storage plans are uncertain, since justification of plutonium storage will depend upon uranium price, plutonium value in LWR's or FBR's, and recovery cost projections. There are indications that the economics tend to favor plutonium storage in the form of spent fuel.[57] Questions related to the economics of the alternatives discussed above are beyond the scope of this study and will not be addressed.

4.5 Spent-Fuel Revenues - Summary

Revenues from spent fuel in terms of uranium and separative work savings can be realized by satisfaction of spent-fuel demand. This demand can be essentially of two types: reprocessing and disposal.

In the disposal case, spent fuel becomes a liability with a negative value. In spent-fuel reprocessing, there are two alternatives possible. In the first alternative, under the environment of a plutonium ban or an incentive to stockpile plutonium for use in fast breeders, reprocessing can be performed in order to recover and sell (reuse) uranium and stockpile plutonium for future uses. In the second alternative, both recovered products, uranium and plutonium, can be promptly recycled.

Plutonium and recovered uranium supply over time depends upon the following factors:

1. Projections of installed capacity of LWR's over time.
2. PWR and BWR installed capacity ratio.
3. Projections of average reactor fuel inventory, load factor, and discharge burn-up.
4. Delay time between spent fuel discharge and plutonium availability, (plutonium availability over time is determined by reprocessing capability).

Obviously, the same factors will determine the savings in uranium and separative work requirements over time.

In order to evaluate revenues from plutonium, the supply of fissile plutonium in discharged spent fuel over time must be estimated. For the purposes of this study,typical discharge data for BWR's and PWR's will be used. The data are based on the assumption that the discharged fuel achieves its full design exposure, which is 27,500 MWd/MTU for the BWR and about 32,600 MWD/MTU for the PWR. These data are summarized in Table 4.8.

Table 4.8. Characteristics of Discharged Fuel.[33]

Discharge batch number	Fissile plutonium [g/Kg U]	
	BWR	PWR
1	4.2	4.6
2	4.8	6.1
3	5.2	6.8
4	5.5	6.9
5	5.9	7.0
Average	5.12	6.28

Depending upon the individual circumstances of spent-fuel discharge, actual cases may differ from the above data. In order to find representative quantities of fissile plutonium contained in discharged spent fuel over time, the ratio of PWR to BWR installed capacity must be known. Since reprocessing capacity is expected to be available in early 1980's, the following assumptions will be made:

1. Since fissile plutonium content diminishes with "age," (period of storage), it will be assumed that the latest batches will be reprocessed first, i.e., a LIFO policy will be applied.
2. The average ratio of BWR to PWR installed capacity since 1980 to 2000 will be assumed equal to 1 to 2.

Under these assumptions, it is found that the fissile plutonium content of spent fuel discharged from typical LWR will be about 5.9 g per Kg of spent fuel. In addition, it is estimated, (see data in Table 4.5), that the plutonium-241 content in fissile plutonium is about 18%.

Plutonium-241 is radioactive and undergoes a beta decay to americium-241 with a half-life equal to 13.2 years. The buildup of americium-241 adversely affects the neutronic value of the plutonium reused in the reactor. Am-241 is also contained in discharged assemblies. For example, in PWR assemblies with an average burn-up of 36,000 MWD/MTU, 3% of the residual Pu-241 is americium-241.[57] During reprocessing, americium is removed but its buildup starts again through continued decay of plutonium-241. Radioactivity of Am-241 can lead to higher handling charges of fuel containing Am-241 resulting in higher fabrication costs of mixed-oxide fuel. Americium removal charges were estimated to be about \$4.8/g of plutonium.[57]

The decrease of fissile plutonium content in the spent fuel due to the decay of plutonium-241 during time t, can be expressed by (see Appendix 1)

$$Pu_f(t) = Pu_f(0)(1 - r(1 - e^{-\lambda t})), \tag{4.8}$$

where

$Pu_f(t)$ = quantity of fissile plutonium, at time t

$Pu_f(0)$ = quantity of fissile plutonium at time t = 0

r = concentration ratio of plutonium-241 to total fissile plutonium, Pu-239 + Pu-241

λ = plutonium-241 decay constant, $\lambda = 0.0525$/year.

For the investigation of spent fuel storage needs over time and location and using a discretized time variable with yearly intervals, the aggregate cumulative loss of fissile plutonium through Pu-241 decay in the stored spent fuel in time period K can be approximated by the expression (see Appendix 1)

$$L_K = [\sum_{j=1}^{K} (S_j - D_j) \sum_{m=0}^{K-j} \ell^m]F, \tag{4.9}$$

where

$$F = r(1 - \ell)P_o, \tag{4.10}$$

and

S_j = amount of spent fuel discharged in period j, MT

D_j = spent fuel demand in period j, MT

ℓ = $e^{-0.0525}$

r = ratio of Pu-241 to Pu-239 and Pu-241

P_o = quantity of fissile plutonium per metric tonne of discharged spent fuel

j = index denoting time period, j = 1, 2, ..., N; the value j = 1 corresponds to the beginning of the planning horizon.

From the discussion above, it is apparent that prompt recycling is advantageous since about 5% of the plutonium-241 corresponding to 1 to 1.5% of fissile plutonium is lost through beta decay each year the fissile plutonium is out of the reactor. The aggregate cumulative loss of fissile plutonium in each year in terms of the loss in savings of uranium feed and separative work requirements will be accounted for in the objective function of the model.

4.5.1 Recovery and Reuse of Uranium with Stockpiling of Plutonium For Future Use

Profit realized under the alternative of the recovery and reuse of uranium with stockpiling of plutonium for future use consists of two components. The first component represents the difference between profit realized by recycling the recovered uranium and reprocessing costs. It will be assumed that those expenditures will occur in the same time period. The second component expresses the difference between profit realized by recycling plutonium in LWR's or by plutonium use for the first loadings of fast breeder reactors at some future date and plutonium storage charges during period between the time of spent-fuel reprocessing and time of plutonium use. The relationship for the profit realized in period k by satisfying a unit quantity of demand, can be written as

$$P(k) = U(k) - R(k) + P_o[1 - r(1 - e^{\lambda (h - k)})]V(h)\ d^{(h - k)} - P_o \sum_{j=k}^{h} C(j)\ d^{(j - k)}, \qquad (4.11)$$

where

$P(k)$ = profit in period k, \$/MTU

$R(k)$ = unit reprocessing cost in period k, \$/MTU

$U(k)$ = value of recovered uranium in period k \$/MTU

$V(h)$ = plutonium value in period w, \$/g Pu fissile

$C(j)$ = plutonium storage costs in period j, \$/g Pu fissile

λ = decay constant of plutonium-241 (= 0.0525 year^{-1})

r = ratio of Pu-241 to Pu-239 + Pu-241 in the discharged fuel

d = discount factor

h = period of fissile plutonium use

P_o = fissile plutonium content in spent fuel, g Pu_f/MTU.

In the above equation, it is implied that plutonium storage costs are proportional to the fissile plutonium content of spent fuel discharged under equilibrium reactor operation. No correction in plutonium storage cost over time is made with respect to plutonium-241 decay. The factor $[1 - r(1 - e^{-\lambda(h - k)})]$ in the expression above represents a correction in the stored quantity of fissile plutonium. This correction is due to the decay of plutonium-241 during storage period (h - k), where h denotes time period when plutonium is recycled and k denotes the time period when plutonium becomes available through reprocessing of spent fuel. The value realized by plutonium recycle and expenses related to plutonium storage will be discounted to the period when the discharged spent fuel was reprocessed.

In the case of prompt uranium recycle and deferred plutonium recycle, it is assumed that plutonium recycle in LWR's is preceded by plutonium storage. Using formulas (4.7), (4.11), and values in Tables 4.1, 4.6, 4.8; spent-fuel value of the reference LWR fuel (in $/MT) is given by

$$\begin{aligned} P(k) = {} & [C_s(k) \times 150.0 + C_f(k) \times 1320.0](1 - \eta_1 - \eta_2) \\ & - R(k) + P_o(1 - r(1 - e^{-\lambda(h - k)}))[C_s(h) \times 0.199 + \\ & + C_f(h) \times 0.1845 - \frac{\Delta fc(h)}{q}] \times d^{(h - k)}(1 - \eta_1 - \eta_2 - \eta_3) \\ & - P_o \sum_{j=k}^{h} C(j)\, d^{(j - k)}, \end{aligned} \tag{4.12}$$

where

$C_s(k)$ = price of separative work unit in period k, \$/Kg SWU

$C_f(k)$ = price of natural uranium feed in period k, \$/Kg

$\frac{\Delta fc(k)}{q}$ = fabrication penalty per gram of fissile plutonium in one Kg of the mixed oxide fuel

η_1 = loss during reprocessing

η_2 = loss during fabrication of MO_2 fuel elements

η_3 = loss of fissile plutonium due to Pu-241 decay during reprocessing and fabrication.

The first term in the expression above denotes profit from reuse of recovered uranium in period k. The second term represents reprocessing costs. The third term reflects profit realized by recycling plutonium in period h. This term includes a correction factor for plutonium-241 decay during the storage period. The fourth term represents fissile plutonium storage costs during the period between reprocessing and plutonium recycle, discounted to the time of reprocessing. The coefficients associated with terms $C_s(h)$, 0.199, and $C_f(h)$, 0.1845, (see Table 4.6), reflect the equivalence of 1 g of fissile plutonium recycled in LWR's to the corresponding quantities of separative work and uranium feed, respectively. These values are computed under the assumption that available plutonium will be recycled uniformly in both BWR and PWR's whose ratio of installed capacity was assumed to be 1 (BWR) to 2 (PWR).

If recovered uranium is recycled promptly and plutonium is stockpiled for use in fast breeders, an estimate of the profit can be found by using a relationship similar to (4.12). To assess revenues associated with plausible plutonium use in the FBR's or expenditures related to spent fuel storage, the value of fissile plutonium in fast breeders must be known. The plutonium value in the fast breeder can be estimated using values which are multiples of the fissile plutonium value when it is recycled in LWR's. The profit realized under this alternative is expressed as

$$\begin{aligned} P(k) = {} & (C_s(k) \times 150.0 + C_f(k) \times 1320.0)(1 - \eta_1 - \eta_2) \\ & - R(k) + B \times P_o[1 - (1 - e^{-\lambda(h - k)})](C_s(h) \times 0.199 \\ & + C_f(h) \times 0.1845)(1 - \eta_1 - \eta_2 - \eta_3) \times d^{(j - k)} \\ & - P_o \sum_{j=k}^{h} C(j)\, d^{(j - k)}, \end{aligned} \tag{4.13}$$

where

B = multiplier expressing relative value of plutonium recycled in the FBR's to that in the LWR's.

The meaning of the other symbols is identical to those defined previously. As it was pointed out in Section 4.2, the value of fissile plutonium in FBR's can range from 100 to 200% of the fissile plutonium value in LWR's.[22,57]

The penalty associated with plutonium-241 decay in stored spent fuel can be approximated in terms of the potential revenues for the case in which this plutonium would be recycled back into LWR's or FBR's. Under the assumption of uniform plutonium recycle in both BWR's and PWR's, whose ratio of installed capacity is about 1:2, the cost of the aggregate cumulative loss of plutonium-241 in the stored fuel in time period k can be expressed by the following formula:

$$L(k) = P_o r(1 - \ell) \sum_{j=1}^{k} (S(j) - D(j)) \sum_{m=0}^{k-j} \ell^m \times$$

$$(C_s(k) \times 0.199 + C_f(k) \times 0.1845), \qquad (4.14)$$

where

L(k) = loss of potential revenue in period k due to decay of Pu-241

S(j) = quantity of spent fuel discharged in period j

D(j) = total spent-fuel demand in period j

ℓ = $e^{-0.0525}$

4.5.2 Reprocessing with Prompt Recycle of Both Uranium and Plutonium

This alternative is a special case of the alternative considering the stockpiling of fissile plutonium. Under this alternative, it will be assumed that both uranium and plutonium will be recycled promptly after they have become available through reprocessing. The fissile plutonium storage charges can be neglected. The profit in period k realized under this alternative can be expressed as:

$$P(k) = (C_s(k) \times 150.0 + C_f(k) \times 1320.0)(1 - \eta_1 - \eta_2)$$
$$- R(k) + P_o(C_s(k) \times 0.199 + C_f(k) \times 0.1845)(1 - \eta_1 - \eta_2 - \eta_3), \qquad (4.15)$$

where meaning of the symbols is identical to those defined previously.

5. MODEL DEVELOPMENT

In the preceding chapters, the crucial factors, both static and dynamic, which constitute the spent-fuel storage problem were identified. In order to assess the system-wide interactions of these factors and the ramifications of the plausible decision alternatives, a realistic model, which structures all of the relevant facets of the spent-fuel problem into a logical decision oriented framework, is developed in this chapter. The model development is preceded by discussion of the crux of the dynamic phenomenon of the spent fuel storage problem.

Both methods, linear and dynamic programming algorithms, can be applied to solving the spent-fuel storage problem. A comparative analysis of both methods with respect to the structure of the problem is presented. Based on the advantages of the linear programming technique (LP) in this particular application, the multistage dynamic spent fuel storage model is transformed into a form amenable to be solved by LP.

5.1 Principal Features of the Spent Fuel Storage Problem

As it was pointed out previously, there has been a substantial accumulation of irradiated fuel over the past several years due to a lack of reprocessing and disposal capability. More nuclear plants are scheduled to be brought on line in the near future. The actual rate of nuclear capacity growth will determine the rate of spent fuel discharge over time. The rate of spent-fuel stockpile generation is determined by the balance between the spent-fuel discharge rate and the demand rate for spent fuel. The rate of spent-fuel back-log, which represents requirements upon storage capacity, can be described by:

$$\frac{\Delta I(t)}{\Delta t} = S(t) - D(t), \qquad (5.1)$$

where

$\Delta I(t)$ = quantity of spent fuel to be stored in time t

Δt = time increment

$S(t)$ = spent-fuel discharge rate in time t

$D(t)$ = spent-fuel demand rate in time t

The complexity of the present and future management of spent-fuel stockpiles is compounded by uncertainty in the spent-fuel discharge and demand rates. The time dependent spent-fuel discharge rate, S(t), is dependent primarily upon the actual future growth of nuclear power and upon operating policies. For example, the recent experience of the nuclear industry, which has manifested itself in cancellation of nuclear plant orders and slippages in the construction schedules,(59) has temporarily postponed a deficiency in spent-fuel storage capacity. Uncertainty in nuclear power growth is also compounded by the uncertainty in the capacity factors actually experienced by the nuclear power plants.

The effects of spent-fuel demand variations on spent-fuel management are of the same importance as the spent-fuel discharge rate variations. The current standstill of reprocessing capability with the lack of spent-fuel disposal capacity has resulted in sharply increased storage requirements. It was estimated that the effect of the lack of reprocessing capability on the storage capacity needs has exceeded that of the nuclear plants installation slippage by a factor of three.[10]

The quantitative analysis of the spent-fuel problem in the preceding chapter has enumerated several feasible options for providing additional spent-fuel storage. There are a number of options for providing additional storage on the reactor sites. These options include the increase in the physical dimensions of the fuel pool, fuel rack expansion at the existing reactors and those installed in the future,[8,12] and also installation of large pools at the multi-reactor sites. Other feasible options for additional storage installation include large multi-regional or multi-utility pools, commercial spent-fuel storage facilities,[21,46] and installation of additional storage facilities associated at the reprocessing plants. It should be pointed out that for off-reactor-site storage facilities, there is an associated transfer of spent fuel which includes expenses for handling and transportation.

In 1976, ERDA surveyed existing and planned storage capacities and concluded that some utilities already have insufficient capacity in their spent-fuel basins to maintain full core discharge capability and that several basins were nearly full, potentially necessitating the shut down of those reactors in the absence of corrective action.[(14)] Reactor shut down must be considered an infeasible solution to the spent-fuel storage problem because of the excessive cost of obtaining replacement power if sufficient replacement energy could be generated. Consequently, the set of feasible solutions include the many combinations of plans for storage capacity expansion and reprocessing plant start-up or disposal prohibition relaxation.

The dynamic nature of the basic structural elements of the spent-fuel storage problem, compounded by uncertainties involved in these elements, renders spent-fuel management highly complex. Hence, the development of a model is preferable to an attempt to generate a simple formula or code. This model should be solved using a versatile technique that can facilitate the determination of spent-fuel storage alternatives on the basis of a suitable criteria. An appropriate criterion is the minimum spent-fuel storage cost.

The modeling of a dynamic spent-fuel storage problem requires some knowledge of the structural properties of a multi-stage dynamic optimization model. These properties are discussed in Appendix 3.

5.2 Formulation of the Spent-Fuel Storage Model

The spent-fuel storage problem is, in essence, a planning problem spanning a number of years. Before a model of the problem can be constructed, some decisions must be made concerning the choices of the length of the planning horizon, the objective and the measure of effectiveness, the decision variables, and the constraints. These choices generally must be made together as one choice often affects another; however, determining what should be maximized or minimized is probably a good starting point.

The only activity during which nuclear fuel generates a revenue is its irradiation in the reactor. Activities related to nuclear fuel before and after its residence in the reactor are essentially expenditure intensive with a net effect of an increase of the fuel cycle costs. Therefore, it seems logical that the approach of minimizing the overall costs related to the spent-fuel management is the most appropriate.

For modeling purposes, the planning horizon should be of sufficient length to include important expected events pertinent to the spent-fuel storage problem such as resumption of reprocessing, plutonium recycle, and the start-up of the commercial fast breeder reactors. Consequently, a planning horizon of three decades is considered. Since most of the currently designed nuclear power plants operate on a cycle in which the reactor annually discharges and replaces approximately one-third of its fuel, a division of the planning horizon into periods of one year duration is appropriate for the problem. The periods will be denoted by the index k, k = 1, 2, ..., N (length of the horizon).

There are several options for storing spent fuel. The spent fuel, after having been "cooled" to allow for decay of short-lived fission products, can either continue to be stored in the fuel pool at the reactor sites or can be shipped and stored in off-reactor-site facilities. The off-reactor-site facilities may be independent pools operated by utilities or owned by independent operators. Also, spent fuel, which is to be reprocessed, can be stored in pools located at the reprocessing plants. The independent pools can be located either near both the reactors and reprocessing plants or at some selected central sites. Since irradiated fuel transportation expenses will be substantial, the location of spent-fuel storage facilities with respect to the location of facilities supporting the ultimate disposition of spent fuel (reprocessing, disposal) and that of power plants should be selected in order to minimize the transportation costs. Also, considerations such as meteorological conditions and seismic stability of geological strata of the site are important in spent-fuel storage site selection. These considerations will limit the number of feasible spent-fuel storage locations.

Storage capability of the fuel tanks at the reactor sites, or reprocessing plant sites, can be increased from the usual capacity of 140% of full core reload by approximately 100% to 800% by redesigning the fuel racks.

The decision variables of the model which will be analyzed are the following:

1. Amount of aggregate on-site fuel tank storage capacity to be added in period k, x_{1k}.
2. Amount of aggregate off-site storage capacity to be added in period k, x_{2k}.
3. Fraction of the amount of spent fuel discharged and "cooled" in period k to be stored in an off-reactor-site storage facility in period k, x_{3k}.

The direct cost parameters assignable to the values of the decision variables can be divided into two classes: first (capital) costs and annual cost rates which denote expenditures over one year period. Among the costs which are incurred only once when an activity takes place (first costs) are the costs of bringing a storage capacity on line, costs of handling spent-fuel, and the costs of transportation and insertion of spent-fuel into storage facilities. Also, the expenditures related to the disposal of spent-fuel or the value realized by satisfying demand are first costs. On the other hand, among the cost rates (intensities of expenditures), there are the costs of holding spent-fuel in storage facilities and the annual loss of value of stored spent-fuel due to plutonium-241 decay.

The construction costs of on- and off-site facilities will vary over time and will be sensitive to escalation of prices for labor and materials. Also, spent-fuel storage, transportation cask rental, and transportation costs will be time dependent. Profit realized by reprocessing spent fuel and reuse of recovered uranium and plutonium will be influenced by variations in reprocessing costs, U_3O_8 feed cost, separative work charge, and plutonium value over time. The estimates of expenses related to spent-fuel storage facilities and forecasts concerning spent fuel value were presented in detail in Chapters 3 and 4. Cost parameters related to the decision variables are summarized below:

c_{1k} = cost of bringing one unit of on-site storage capacity on line in period k

c_{2k} = cost of bringing one unit of off-site storage capacity on line in period k

c_{3k} = cost in period k of handling and implanting a unit of spent fuel in an on-site storage facility

c_{4k} = cost of cask rental, handling, transportation and implanting of one spent fuel unit in an off-site storage facility in period k

c_{5k} = annual storage cost rate of one fuel unit stored in an on-site storage facility in period k

c_{6k} = annual storage cost rate of one fuel unit stored in an off-site facility in period k

c_{7k} = plutonium-241 decay cost in period k per one unit of spent fuel

p_k = value of one spent fuel unit reprocessed in period k.

The values of the decision variables and consequently of the overall cost of the spent-fuel storage program will be dependent upon the quantity of spent fuel discharged over time and spent-fuel demand.

The spent-fuel discharge rate is proportional to the nuclear fuel demand rate for the cumulative nuclear plant installations over time. The nuclear fuel demand over time is determined by the types of nuclear power plants, their mix, and their installed capacities. Under a one year refueling cycle, the spent-fuel discharge rate lags behind that of refueling by approximately one year. The quantity of spent fuel discharged in time period k will be denoted by S_k.

Spent fuel can be considered to be a by-product of electrical power generation by nuclear power plants. Spent-fuel demand over time is therefore determined by the current economy of reuse of recovered uranium and plutonium from spent fuel and the status of the reprocessing industry. In the case of plutonium recycling, adequate support of mixed-oxide fuel fabrication facilities is needed. Economic and political considerations may also lead to disposal of spent fuel as a waste. The aggregate spent-fuel demand in time period k will be an input parameter and will be denoted by D_k. In the initial investigation of the model behavior, D_k will be assumed to be zero in every time period. Subsequent analysis will examine the consequences of relaxing this assumption but will not define the specific uses of the spent fuel.

Using the elements defined in the previous paragraphs, the objective function which reflects the consequences of adherence to alternative decision strategies can be constructed. Actually, the optimization objective is to find the optimal sequence of decision variables x_{1k}, x_{2k}, x_{3k} such that the cost incurred as a consequence of these decisions over the planning horizon is a minimum. This objective is to minimize

$$\sum_{k=1}^{N} \{c_{1k}\, x_{1k} + c_{2k}\, x_{2k} + c_{3k}(T_k(1 - x_{3k})) + c_{4k}(T_k\, x_{3k})$$

$$c_{5k} \sum_{j=1}^{k} (T_j(1 - x_{3j}) - D_{1j}) + c_{6k} \sum_{j=1}^{k} (T_j\, x_{3j} - D_{2j})$$

$$c_{7k} \sum_{j=1}^{K} (S_j - D_j) - p_k\, D_k\}, \qquad (5.2)$$

where

$$T_k = \max\,(S_k - D_k, 0). \qquad (5.3)$$

The first term in the objective function denotes the expenditure associated with bringing on-site storage capacity x_{1k} on line in period k. The term, $c_{2k}\, x_{2k}$, is the cost of off-site storage capacity. The third and fourth terms represent expenditures incurred in handling, transporting, and implanting fractions of the amount of spent fuel discharged in excess of demand into on- and off-site storage facilities in period k. The expenditures associated with spent fuel storage in off and on-site storage facilities over time have significant impact on the economy of the back end of the fuel cycle. These holding costs are represented by two terms. The term associated with cost c_{5k} reflects annual the holding cost for spent fuel stored in an on-site storage facility in period k. Off-site holding costs are expressed by the term associated with the cost parameter c_{6k}. Since plutonium-241, which is contained in spent fuel, has a half-life of 13.2 years, the value of spent fuel diminishes with extended storage. The term, $c_{7k} \sum_{j=1}^{k} (S_j - D_j)$, approximates the penalty incurred due to plutonium decay in stored fuel in period k. The last term is the profit realized in period k by satisfying spent-fuel demand in the same period. The objective function written in the form above can be further algebraically manipulated. Specifically, the order of summation in terms involving double summation operators of the type $\sum_{k=1}^{N} \sum_{j=1}^{k} a_j b_k$ can be inverted with appropriate adjustment of summation limits to yield a double sum in the form $\sum_{k=1}^{N} \sum_{j=k}^{N} a_k b_j$.

The objective function can be then written in the following form:

$$
\begin{aligned}
I(\underline{x}) = \text{Min} \sum_{k=1}^{N} \{ & c_{1k} x_{1k} + c_{2k} x_{2k} + c_{3k}(T_k(1 - x_{3k})) + c_{4k}(T_k x_{3k}) + \\
& (T_k(1 - x_{3k}) - D_{1k}) \sum_{j=k}^{N} c_{5j} + (T_k x_{3k} - D_{2k}) \sum_{j=k}^{N} c_{6j} \\
& + (S_k - D_k) \sum_{j=k}^{N} c_{7j} - p_k D_k \}
\end{aligned}
\tag{5.4}
$$

By regrouping the terms associated with individual decision variables the objective function assumes the form:

$$I(\underline{x}) = \text{Min} \sum_{k=1}^{N} \{[c_{1k}\, x_{1k} + c_{2k}\, x_{2k} + (c_{4k} - c_{3k} + \sum_{j=k}^{N} (c_{6j} - c_{5j}))$$

$$\times T_k\, x_{3k}] + [c_{3k}\, T_k + (T_k - D_k) \sum_{j=k}^{N} c_{5j} - D_{2k} \sum_{j=k}^{N} c_{6j}$$

$$(S_k - D_k) \sum_{j=k}^{N} c_{7j} - p_k\, D_k]\}. \qquad (5.5)$$

In this form, only terms within the first brackets involve decision variables. The terms in the second brackets are constant with respect to the spent-fuel storage decision variables. Thus, the optimal policy for spent-fuel storage over time can be found by optimization of the objective function:

$$I(\underline{x}) = \text{Min} \sum_{k=1}^{N} \{c_{1k}\, x_{1k} + c_{2k}\, x_{2k} + (c_{4k} - c_{3k} + \sum_{j=k}^{N} (c_{6j} - c_{5j}))$$

$$\times\ T_k\, x_{3k}\}. \qquad (5.6)$$

The status of the spent-fuel storage system at any time is determined by the balance between the spent-fuel discharge and demand rates. A discrepancy in these rates creates an accumulation of spent-fuel material in the system. In view of the on-site and off-site capacity available, this accumulation at a point in time can be represented by two state variables:

1. the quantity of unused on-reactor-site storage capacity at the beginning of period k, u_{1k}.

2. the quantity of unused off-site storage capacity at the beginning of period k, u_{2k}.

The evolution of the system status over time will be determined by the exogenous input parameters, rates of fuel discharge and fuel demand, and the values of decision variables at each stage (time period).

The transition relationship describing change in the quantity of the unused on-reactor-site storage capacity during stage k is

$$u_{1k} = u_{1,k-1} + x_{1k} + z_{1k} - T_k(1 - x_{3k}) + D_{1k}, \qquad (5.7)$$

where D_{1k} denotes demand on the on-site spent-fuel inventory in excess of the amount of spent fuel discharged in period k. The term, z_{1k}, denotes additional storage capacity brought on line in period k as part of newly installed nuclear capacity. The term, T_k, is defined by the relationship

$$T_k = \max(S_k - D_k, 0). \qquad (5.8)$$

The quantity T_k in the relationship with decision variable x_{3k} (term T_k $(1 - x_{3k})$) shows that a decision to transfer spent fuel to an off-site storage facility will be in effect only when demand for spent fuel is less than the amount of spent fuel discharged in the same period. If demand for spent fuel exceeds the amount of spent fuel discharged, no transfer of spent fuel will take place and the storage capability will be increased by an amount equal to D_{1k}.

The transition relationship (5.7) expresses the balance between use (expressed by term $T_k(1 - x_{3k})$) and acquisition of storage capacity in period k. The requirement that storage needs must be met in each time period can be expressed by the inequality

$$u_{1k} \geq 0 \ \forall \ . \tag{5.9}$$

The change of status for the unused off-site storage capacity is given by transition relationship

$$u_{2k} = u_{2,k-1} + x_{2k} + z_{2k} - T_k \, x_{3k} + D_{2k}, \tag{5.10}$$

where z_{2k} denotes the off-site spent-fuel storage capacity brought on line in period k apart from the optimal policy which will be found by the model. The incorporation of this input variable in the above relationship will permit evaluation of the impact on spent-fuel storage situation which will be brought on by announced expansions of spent-fuel storage basins associated with the reprocessing plants or construction of independent pools. The term, D_{2k}, expresses demand for spent fuel stored in an off-site storage facility. This demand is considered non-negative in period k, only when spent-fuel demand will exceed the amount of spent fuel discharged in the same period. Total spent fuel demand, on- and off-site demands, and spent-fuel supply are in a relationship which can be expressed by

$$D_{1k} + D_{2k} = \max\,(D_k - S_k,\ 0) \tag{5.11}$$

where both D_{1k} and D_{2k} are assumed to be non-negative.

Relation (5.10) represents a balance between the use and acquisition of off-site storage capacity in period k. It is required that the resulting unused off-site storage capacity in period k be non-negative, i.e.,

$$u_{2k} \geq 0 \ \forall_k \ . \tag{5.12}$$

The inequalities (5.10) and (5.12), which are constraints on the optimization problem, represent the requirement that storage needs must be met in all time periods.

State variable transformations (5.7) and (5.10) with requirements (5.9) and (5.12) implicitly express constraints on combinations of decision variables x_{1k}, x_{2k} and x_{3k} in terms of the unused storage capacities u_{1k} and u_{2k} for each time period. In addition to these constraints, there is a constraint on the range of variable x_{3k} for each period k, i.e.,

$$0 \leq x_{3k} \leq 1 \ \forall_k \ . \tag{5.13}$$

Also, the influence of constraints representing upper bounds on the on-site, L_{1k}, and off-site, L_{2k}, storage capacity expansion over time is investigated using the model. The constraints reflecting technological or other limits on spent-fuel storage capacity expansion can be expressed as

$$0 \le x_{1k} \le L_{1k} \qquad \forall_k , \qquad 0 \le x_{2k} \le L_{2k} , \tag{5.14}$$

where L_{1k} was defined in Chapter 3, Section 3.4.1, Equation (3.2), as

$$L_{1k} = \Delta R_k (1.4\ M - 1)\ FCR .$$

For convenience, the spent-fuel storage model can be summarized as:

Find the function

$$I(\underline{x}) = \text{Min} \sum_{k=1}^{N} \{[c_{1k}\ x_{1k} + c_{2k}\ x_{2k} + (c_{4k} - c_{3k} + \sum_{j=k}^{N} (c_{6j} - c_{5j}))\ T_k\ x_{3k}] + [c_{3k}\ T_k + (T_k - D_{1k}) \sum_{j=k}^{N} c_{5j} - D_{2k} \sum_{j=k}^{N} c_{6j} + (S_k - D_k) \sum_{j=k}^{N} c_{7j} - p_k\ D_k]\} \tag{5.15}$$

over the set of vectors $(\underline{X}_1, \underline{X}_2, \ldots, \underline{X}_N)$, where $\underline{X}_k = (x_{1k}, x_{2k}, x_{3k})$, and subject to constraints

$$u_{1k} = u_{1,k-1} + x_{1k} + z_{1k} - T_k(1 - x_{3k}) + D_{1k}$$

$$u_{2k} = u_{2,k-1} + x_{2k} + z_{2k} - T_k\ x_{3k} + D_{2k} , \tag{5.16}$$

and

$$0 \leq x_{1k} \leq L_{1k}$$

$$0 \leq x_{2k} \leq L_{2k} \qquad \forall k$$

$$0 \leq x_{3k} \leq 1 \, . \tag{5.17}$$

The requirements for meeting the storage needs at all times are expressed by the constraints

$$u_{1k}, \, u_{2k} \geq 0 \quad \forall k. \tag{5.18}$$

The initial conditions appearing in the transition relationships (5.16) are expressed for both on-site and off-site storage as u_{10} and u_{20}, respectively. Only the first term of the objective function (5.15) is dependent upon the decision variables.

5.3 Analysis of the Model Structure

The spent-fuel storage model presented in Section 5.2 is amenable to solution by both static and dynamic optimization techniques. In general, the choice between the techniques depends on the structural characteristics of the model in question. Several special features of the spent-fuel storage model can be observed.

First, it should be pointed out that the state transition relationships (5.16) and the objective function (5.15) are linear in terms of the state variables u_k and the decision variables, x_{ik}. Also all constraints on decision variables (5.17) are linear.

Another property of the model is the fact that the state variables depend only on the initial state (u_{10}, u_{20}) and past decision variables. This feature is indicative of sparse coupling among the decision variables over the planning horizon. Finally, it is noted that in effect, an open-loop solution is sought, i.e., a solution which depends solely on the initial state.

These properties make the model amenable to solution by dynamic programming (DP).[60,61] Applicability of DP hinges upon two basic assumptions. The first is the requirement that the state variables exhibit the state separation property.[62,63] This property requires that future behavior of the system may be deduced from the state transition equations and the present state without reference to past states. It is evident that the spent-fuel storage model exhibits this property. The other conditions are the properties of separability and monotonicity of the objective function.[61,63] These conditions allow decomposition of the objective function into a functional form such that the dynamic recursive algorithm can be applied. For illustrative purposes, the derivation of functional form of the objective function is shown in Appendix 4.

The computational procedures using a dynamic programming algorithm are appealing for a number of reasons. Extremely general types of system equations, objective functions, and constraints can be handled. On the other hand, computational requirements become excessive when the technique is applied to large problems.[63,64]

Special properties of the spent-fuel storage model, namely linearity of the objective function and constraints, make the problem amenable to solution by a linear programming algorithm. The linear programming approach also offers the advantage of allowing the decision variables to be continuous. It should be pointed out that decision variables of the spent-fuel storage model represent on-site and off-site capacity additions in an aggregate form. However, a necessity may arise requiring the choice of storing spent-fuel among several off-site storage facilities at different locations. The handling of this situation would require additional decision and state variables. Additional constraints would have to be included. The addition of decision variables to a model without modifying the computational procedure can be easily accomplished when a linear programming approach is used. On the other hand, a dynamic programming algorithm does not possess the same flexibility. Computational requirements increase exponentially with the number of state variables (curse of dimensionality[60]), and special algorithmic procedures are required to make the computations tractable.[63]

In view of the linear properties of the spent-fuel storage model, a linear programming solution approach was chosen. This choice was also affected by desirability to prepare a versatile and flexible computational tool, (in effect, a computer-oriented information system) allowing further development, if a more detailed picture of the spent-fuel storage problem were needed.

Since proper application of linear programming (LP) to the spent-fuel storage model requires some knowledge of the structure and limitations of LP, a brief description of the linear programming theory is provided in Appendix 5.

5.4 Linear Programming Formulation of the Spent-Fuel Storage Problem

As it was pointed out previously, the spent-fuel storage model displays the properties of linearity of the objective function and state transition relationships in terms of the decision and state variables. Also, constraints on the state and decision variables are linear. The spent-fuel storage model exhibits a feature that the optimal on-site and off-site storage capacity additions over time are dependent only on the initial status of both on-site and off-site unused storage capacities at the beginning of the planning.

In order to cast the dynamic multistage optimization problem defined by relationships (5.15) through (5.18) into an LP model, which is stated in Appendix 5 by relationships (1) through (3), several transformations must be performed.

First, new mathematical programming variables must be defined. These variables correspond to the original decision variables at each time period. In this transformation, the double index ik, of decision variable x_{ik} can be expressed as a single index according to transformation

$$x_{ik} \rightarrow x_{I \cdot (k-1) + i},$$

where I is the number of the stage variables,

and

$$i = 1, 2, I = 3$$
$$k = 1, 2, \ldots, N .$$

However, for the sake of clarity in the model interpretation a double index, ik, will be maintained.

A second transformation must be performed on the constraints (5.18) involving state variables u_{1k}, u_{2k}. These state variables must be expressed in terms of the decision variables x_{ik} (i = 1, 2, 3; k = 1, 2, ..., N) and the initial state (u_{10}, u_{20}) by recursive application of the transition relationships (5.16). This process transforms the set (5.18) into constraints expressed as

$$\sum_{j=1}^{k} (x_{1j} + T_j\, x_{3j}) \geq \sum_{j=1}^{k} (S_j - z_{1j} - D_{1j}) - u_{10}$$

$$\sum_{j=1}^{k} (x_{2j} - T_j\, x_{3j}) \geq - \sum_{j=1}^{k} (z_{2j} + D_{2j}) - u_{20} \qquad (5.19)$$

The constraints (5.17) can be expressed as two sets. The first set can be defined by

$$x_{1k} \leq L_{1k}$$
$$x_{2k} \leq L_{2k}$$
$$x_{3k} \leq 1. \qquad (5.20)$$

What remains are the non-negativity requirements:

$$x_{1k}, x_{2k}, x_{3k} \geq 0 \tag{5.21}$$

In summary, the dynamic multistage optimization spent-fuel storage model is transformed into the linear programming model defined by the objective function (5.15) and the constraints (5.19) through (5.21). In this form the model is amenable to solution by any LP algorithm.

6. ACTUAL APPLICATION OF THE SPENT-FUEL STORAGE MODEL

The linear model of the spent-fuel storage problem developed in Chapter 5 is applied to the optimization of spent-fuel storage capacity needs. Two aggregate on-site and off-site storage facilities are considered. This chapter summarizes the principal data which are used in the actual application.

6.1 Model and Data Summary

The optimization consists of finding the most economic plan for on-site and off-site storage capacity allocation over time. The third decision which must be made is to determine what fraction of spent-fuel discharged in a period is to be transferred to an off-site facility for storage. Various values of the exogenous parameters and spent-fuel supply and demand scenarios define particular problems each of which is solved separately.

In order to apply the model to the spent-fuel storage problem it is necessary to use the data cited in Chapters 3 and 4 and to identify the model parameters. The first of the parameters required are the values of the planned storage capacity expansion, z_{1k}, resulting from growth of nuclear capacity installations. The values of these parameters together with the scheduled growth of nuclear capacity are listed in Table 6.1.

Storage needs are examined for several situations with different upper limits for on-site capacity expansion over time. For the

Table 6.1. On-site Storage Capacity Data and Constraints

Year	POW [10^3 MWe]	z_1 [MT]	L_1 [MT]			
			M = 3	M = 2.5	M = 2	M = 1.5
1976	6.14	280.0	1959.9	1469.9	979.9	490.
1977	6.87	313.3	2192.9	1644.7	1096.5	548.2
1978	4.0	182.4	1276.8	951.6	638.4	319.2
1979	4.42	201.6	1410.9	1058.1	705.4	352.7
1980	18.31	835.0	5844.6	4383.4	2922.3	1461.1
1981	23.5	1071.6	7501.2	5625.9	3750.6	1875.3
1982	14.27	650.7	4555.0	3416.2	2277.5	1138.7
1983	26.71	1218.0	8525.8	6394.4	4262.9	2131.5
1984	27.2	1240.3	8682.2	6511.7	4341.1	2170.6
1985	25.6	1167.4	8171.5	6128.6	4085.8	2042.9
1986	28.9	1317.8	9224.9	6918.7	4612.4	2306.2
1987	29.84	1360.7	9524.9	7143.7	4762.5	2381.2
1988	30.6	1395.4	9767.5	7325.6	4883.8	2441.9
1989	34.6	1577.8	11044.3	8283.2	5522.2	2761.1
1990	36.04	1643.4	11504.0	8628.	5752.0	2876.0
1991	34.6	1577.8	11044.3	8283.2	5522.2	2761.1
1992	35.46	1617.0	11318.8	8489.1	5659.4	2829.7
1993	34.7	1582.3	11076.2	8307.2	5538.1	2769.1
1994	34.6	1577.8	11044.3	8283.2	5522.2	2761.1
1995	32.98	1503.9	10527.2	7895.4	5263.6	2631.8
1996	32.13	1465.1	10255.9	7691.9	5127.9	2564.0
1997	31.3	1427.3	1991.0	7493.2	4995.5	2497.7
1998	29.5	1365.2	7416.4	7062.3	4708.2	2354.1
1999	28.31	1291.0	9036.6	6777.4	4518.3	2259.1
2000	27.46	1252.2	8765.2	6573.9	4382.6	2191.3

Legend: POW = LWR capacity increment(15)

z_1 = planned on-site storage expansion

L_1 = upper limit on on-site capacity expansion particular cases analyzed here, the on-site storage expansion is associated with the installation of new reactors and is determined using the projected growth of nuclear capacity.[15] It is assumed that the storage capacity associated with new power reactors can be expanded to an upper limit given by the technological limitations for the installation of high-capacity fuel storage racks. Five cases are considered. The first case assumes no limitation for on-site storage capacity expansion (notation $M = \infty$). The other cases assume expansion limits from 1.5 to 3 times the standard reactor storage pool capacity which is taken to be 140% of full core.[38] These cases are denoted by the factors $M = 1.5$, 2, 2.5, and 3. The upper limits for on-site capacity expansion are shown in Table 6.1.

About 1.5 to 3 years are required from decision to installation of the high-density spent-fuel storage racks.[8] The off-site capacity expansion is considered unconstrained. The scheduled growth of nuclear power capacity installation is used to estimate the quantity of spent fuel discharged annually. These values are displayed in Table 6.2 and Figure 6.1.

It should be noted that the values for the spent-fuel discharge rates, S_k, for the years 1976-1985 were obtained from ERDA projections.[5] Those for the years 1986-2000 are based upon government projections of nuclear power growth,[15] Scenario D, where the amounts were reduced by 15% by taking into account the current trends characterized by slippages and cancellations of nuclear power plant orders.

Table 6.2. Spent Fuel Storage Requirements

Year	Spent fuel storage requirements [MT]			
	Zero demand (S_k)	Optimistic forecast	Realistic forecast	Pessimistic forecast
1976	874.4	874.4	874.4	874.4
1977	1117.5	1117.5	1117.5	1117.5
1978	1506.5	1506.5	1506.5	1506.5
1979	1773.8	1398.8	1773.8	1773.8
1980	2018.1	893.1	2018.1	2018.1
1981	2223.	348.	1848.	2223.
1982	2444.8	194.8	1319.8	2444.8
1983	3220.6	970.6	1345.6	2845.6
1984	3977.8	1727.8	1727.8	2852.8
1985	4376.3	1376.3	2126.3	2501.3
1986	5326.7	1326.9	3076.9	3076.9
1987	6094.6	1344.6	3094.6	3844.6
1988	6918.2	1168.2	2918.2	4668.2
1989	7856.6	2106.6	3106.6	4856.6
1990	8777.6	3027.6	3027.6	4777.6
1991	9815.	4065.	4065.0	5065.
1992	10896.2	5146.2	5146.2	5146.2
1993	11934.	6184.	6184.	6184.
1994	12999.4	7249.4	7249.4	7249.4
1995	14037.8	8287.8	8287.8	8287.8
1996	15078.2	9328.2	9328.2	9328.2
1997	16067.6	10317.6	10317.6	10317.6
1998	17031.5	11281.5	11281.5	11281.5
1999	17985.9	12205.9	12235.9	12235.9
2000	18872.6	13122.6	13122.6	13122.6

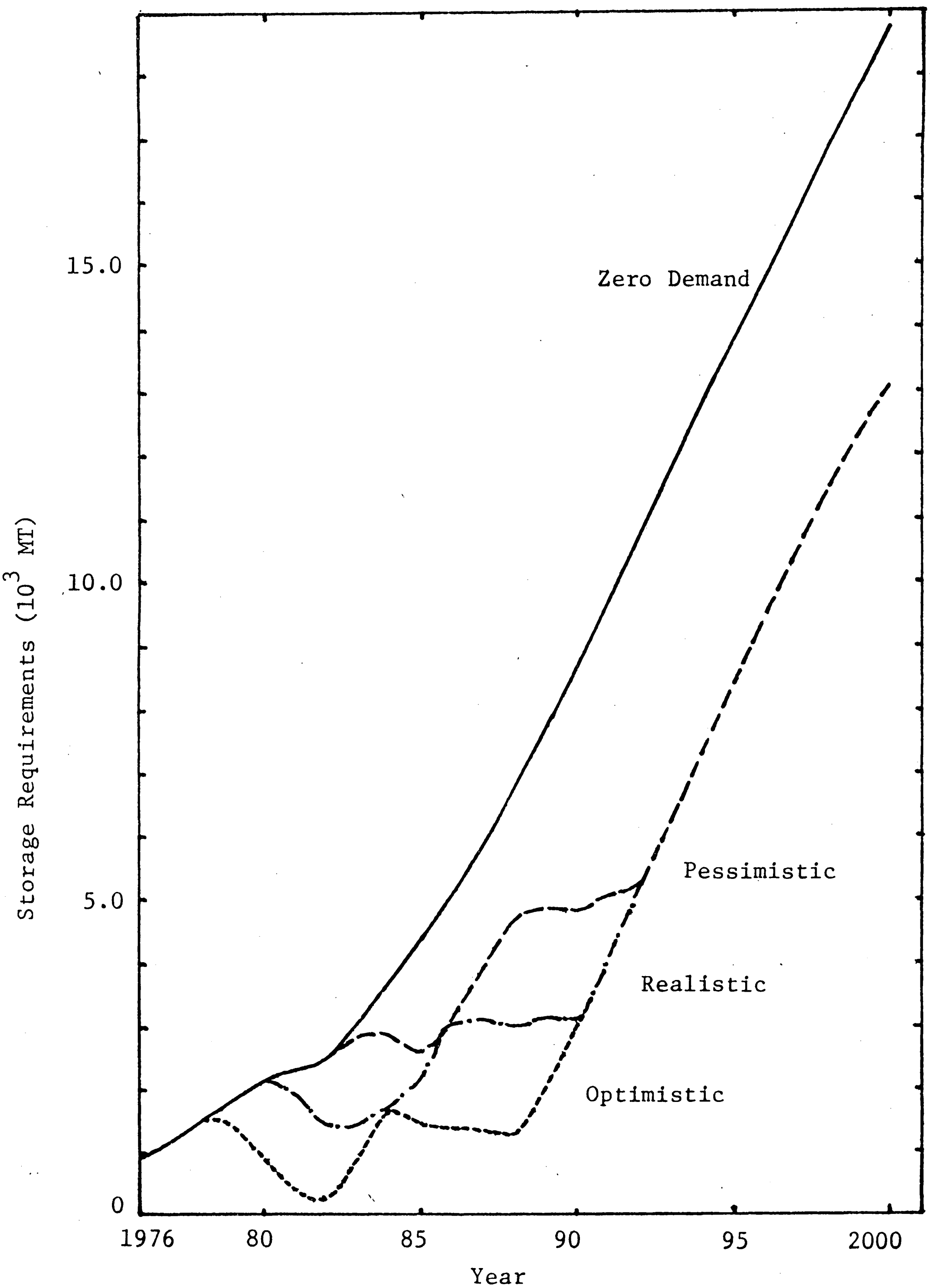


Figure 6.1. Spent Fuel Storage Requirements.

The amount of spent fuel to be stored over time may be reduced by spent fuel demand either for reprocessing or for disposal. In the case of no reprocessing or the absence of the spent-fuel disposal capability, the amount of spent fuel stored over time corresponds to the spent-fuel discharge rate. Spent-fuel storage capacity needs are investigated under four different scenarios labeled:

1. Zero spent-fuel demand case
2. Pessimistic reprocessing forecast
3. Realistic reprocessing forecast
4. Optimistic reprocessing forecast

On the basis of the current status of the fuel cycle characterized by the halt in the construction of the reprocessing plants, it was projected that reprocessing will not occur prior to 1980 or 1981.(10) Three estimates of reprocessing start-up dates were used to evaluate spent fuel storage expansion strategies. The optimistic reprocessing forecast assumes that reprocessing can be initiated in mid-1979. The realistic forecast assumes that reprocessing will start-up in 1981. The start-up in 1983 is included as an pessimistic forecast. The reprocessing program is represented by four reprocessing plants coming on line with a lag time of three years. It is projected the first plant operational will be the AGNS Barnwell Plant (1500 MT capacity), which will be followed by NFS West Valley Plant (750 MT) and Exxon Plant with 2000 MT annual reprocessing capacity. This program is assumed to be followed by a fourth plant with capacity of 1500 MT. The reprocessing capability for the three forecasts is summarized in Table 6.3.

It is assumed that spent-fuel reprocessing would conform to a LIFO (Last-In-First-Out) inventory withdrawal policy for stored spent fuel. This means that the spent fuel which is discharged last is reprocessed first. This policy can be justified on an economic basis, considering the fact that during storage some of the valuable fissile isotope, plutonium-241, is lost due to decay at a rate of about 5% per year (per unit of fissile plutonium contained in LWR spent fuel discharged under equilibrium, the loss is about 1% per year). Reprocessing of spent fuel reduces the net amount of spent fuel which is to be stored in the storage facilities. The net amount of spent-fuel storage under all scenarios is displayed in Table 6.3 and Figure 6.1.

The remaining capacity parameters are the initial quantities of available on-site and off-site storage capacity. At the beginning of 1976 there were 892.0 MT of unused on-site storage capacity and 360.0 MT of available off-site capacity.[10]

The model now requires only the values of cost parameters. These costs can be divided into two classes. The first class includes cost parameters related to storage capacity installations including handling, transportation, and spent-fuel storage costs for both the on- and off-site storage facilities. These costs are summarized in Table 6.4.

Note that parameters associated with handling and transportation

Table 6.3. Reprocessing Program Forecast

Year	Reprocessing Capacity [MT]		
	Optimistic	Realistic	Pessimistic
1976	--	--	--
1977	--	--	--
1978	--	--	--
1979	375	--	--
1980	1125	--	--
1981	1875	375	--
1982	2250	1125	--
1983	2250	1875	375
1984	2250	2250	1125
1985	3000	2250	1875
1986	4000	2250	2250
1987	4750	3000	2250
1988	5750	4000	2250
1989	5750	4750	3000
1990	5750	5750	4000
1991	5750	5750	4750
1992	5750	5750	5750
1993	5750	5750	5750
1994	5750	5750	5750
1995	5750	5750	5750
1996	5750	5750	5750
1997	5750	5750	5750
1998	5750	5750	5750
1999	5750	5750	5750
2000	5750	5750	5750

Table 6.4. Spent-Fuel Storage Cost Components

Cost Component	Value		Ref.
On-site capacity cost, [$/MT]	c_1	5500.0	(44)
Off-site capacity cost, [$/MT]	c_2	20000.0	(57)
On-site handling cost, [$/MT]	c_3	---	--
Off-site handling & transportation, [$/MT/mile]	c_4	---	--
On-site storage cost rate, [$/MT-year]	c_5	3500.0	(44)
Off-site storage cost rate, [$/MT-year]	c_6	10000.0	(4)

costs were assumed to be zero. This assumption is justified using the following reasoning. The model solves for spent-fuel storage expansion under several spent-fuel storage requirement schedules where the expected final disposition of spent fuel is reprocessing and recycling of the unused fissile isotopes of uranium and plutonium. In view of the fact that off-site storage facilities are assumed to be associated with the reprocessing plants and that all spent fuel would be eventually transported to those facilities for reprocessing, transportation and handling costs are common to all alternatives. Thus, transportation and handling charges do not have any effect on the decision. The effect of postponements of these charges over time is neglected.

The second class of costs are those costs and values related to spent-fuel reprocessing and to the recycling of uranium and plutonium back into the fuel cycle. These costs and revenues are summarized in Table 6.5. The spent-fuel values in Table 6.5 are derived using equation (4.15) and uranium and separative work price projections which are displayed in Tables 4.2 and 4.3. The cost of decision alternatives is evaluated in 1976 dollars using the present worth concept applying a 10% discount rate.

Some remarks on the influence of discounting on the sequential models are appropriate here. The discounting procedure expresses the terms of the exchange of future against present good and also the chance of termination of the decision problem. In effect, discounting deemphasizes the importance of the distant future with

Table 6.5. LWR Spent-Fuel Reprocessing Cost and Value Forecasts

Year	Cost and Value Factors [$/MTU]		
	Reprocessing Cost	Spent Fuel Value	Net Profit
1976	170000.0	-134325.5	-35674.5
1977	182500.0	-179127.3	- 3372.7
1978	195000.0	223927.6	28927.6
1979	207500.0	268730.8	61230.8
1980	220000.0	313531.1	93531.1
1981	230600.0	335317.8	104717.3
1982	241200.0	357103.5	115903.5
1983	251800.0	379127.6	127327.6
1984	262400.0	400916.7	138516.7
1985	273000.0	422700.0	149700.0
1986	287200.0	433828.2	146628.2
1987	301400.0	444957.9	143557.9
1988	315500.0	456179.7	140679.7
1989	329800.0	467261.8	137461.8
1990	344000.0	478342.4	134342.4
1991	355800.0	488709.6	132909.6
1992	367600.0	499073.8	131473.8
1993	379400.0	509443.8	130043.8
1994	391200.0	519805.2	128605.2
1995	403000.0	530172.3	127172.3
1996	418000.0	541589.2	123589.2
1997	433000.0	552998.9	119998.9
1998	448000.0	564412.9	116412.9
1999	463000.0	575822.6	112822.6
2000	478000.0	587239.5	109239.5

respect to the beginning and its near-term future. In application to the multistage dynamic problems, the discounting procedure smoothes out the end-effect of the finite horizon.

7. RESULTS

Several situations were analyzed using the LP model in order to compare cost effective storage expansion programs under different spent fuel demand situations and also to investigate the effect of varying certain parameters in the linear model.

The discussion of the results is divided into four sections. The results for the scenario assuming no demand on spent fuel are presented in Section 7.1. Sections 7.2 through 7.4 present discussion of the optimal spent-fuel storage expansion plans for three reprocessing scenarios in terms of the timing of the reinitiation of reprocessing. Under the scenarios arbitrarily labeled as Pessimistic, Realistic, and Optimistic, reprocessing is expected to be resumed in mid-1983, 1981, and 1979, respectively. The graphical display of the results is presented in Section 7.5.

The problems were solved using the MPS III system which was implemented on the IBM/370 Model 1585 computer. The execution time for a typical run was on order of three minutes.

7.1 The Zero Demand Case

The zero demand case in which all discharged fuel from power reactors over the planning horizon is stored in water-pool on-site and off-site storage facilities can be considered as a hypothetical reference case against which the spent-fuel storage needs resulting from the scenarios assuming spent-fuel reprocessing can be compared.

The zero demand case implicitly assumes that the decision whether to reprocess spent fuel or dispose of it as a high-level waste is postponed to the end of the planning horizon. As a matter of fact, the present standstill in reprocessing capability and the lack of disposal facilities for high-level waste in the form of LWR spent fuel represent the situation in which there is no demand upon spent-fuel supplies while neither its salvage value nor disposal charge is determined. The zero demand case characterizes the present status of regulatory indecision, resulting in the current delay of the closed fuel cycle.

The cost optimal plan was calculated for various factors representing technological limits on capacity expansion of the standard-design-spent-fuel racks in new plants. Since installation of high-capacity racks in the reactor-site spent-fuel storage pools is time-consuming and expensive in a tight storage situation, it was assumed that high-capacity racks would be most easily installed in new power plants coming on line. The growth rate of nuclear power installations over time not only determines the spent-fuel discharge rate but also the amount of storage capacity brought on line in each time period. The sensitivity of the solution and cost of the storage expansion program is studied in terms of the magnitude of expansion of the capacity of standard spent-fuel racks. Table 7.1 and Figures 7.1-7.8 show the variation in the optimal storage expansion plan over time in terms of the constraints on on-site storage expansion.

Table 7.1. Solutions - Zero Demand Case

Year	M = ∞			M = 4			M = 3		
	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction
1976	--	--	--	--	--	--	--	--	--
1977	506.6	--	--	506.6	--	--	715.3	--	--
1978	1324.1	--	--	1324.1	--	--	1276.8	--	--
1979	1572.2	--	--	1572.2	--	--	1410.9	--	--
1980	1183.2	--	--	1183.2	--	--	1183.2	--	--
1981	1151.4	--	--	1151.4	--	--	1151.4	--	--
1982	1794.1	--	--	1794.1	--	--	1794.1	--	--
1983	2002.6	--	--	2002.6	--	--	2002.6	--	--
1984	2737.5	--	--	2737.5	--	--	2737.5	--	--
1985	3208.9	--	--	3208.9	--	--	6659.8	--	--
1986	4009.1	--	--	4009.1	--	--	9224.9	--	--
1987	4733.8	--	--	4733.8	--	--	9524.9	--	--
1988	5522.8	--	--	5522.8	--	--	9767.5	--	--
1989	6278.8	--	--	6278.8	--	--	11044.3	--	--
1990	7134.2	--	--	7134.2	--	--	11504.0	--	--
1991	8237.2	--	--	8237.2	--	--	11044.3	--	--
1992	9279.2	--	--	9279.2	--	--	11318.8	--	--
1993	10351.7	--	--	10351.7	--	--	11076.2	--	--
1994	11421.6	--	--	14457.2	--	--	11044.3	--	--
1995	12533.9	--	--	15790.8	--	--	10527.2	--	--
1996	13613.1	--	--	15583.8	--	--	10255.9	--	--
1997	14640.3	--	--	14986.4	--	--	9991.0	--	--
1998	15686.3	--	--	14124.6	--	--	9416.4	--	--
1999	16784.9	--	--	13554.8	--	--	9036.6	--	--
2000	17530.5	--	--	13147.8	--	0.04	8765.2	--	0.04

Legends: x_1 = on-site capacity installation
x_2 = off-site capacity installation
x_3 = fraction of spent fuel transferred off-site.

Table 7.1 (Continued). Solutions - Zero Demand Case

Year	M = 2.5			M = 2			M = 1.5		
	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction
1976	1469.9	--	--	979.9	--	--	490.	--	--
1977	1644.7	--	--	1096.5	--	--	548.2	--	--
1978	957.6	--	--	638.4	--	--	319.2	--	.31
1979	1058.1	--	--	705.4	--	--	352.7	927.9	.69
1980	4383.4	--	--	2922.3	--	--	1461.1	--	--
1981	5625.9	--	--	3750.6	--	--	1875.3	--	--
1982	3416.2	--	--	2277.5	--	--	1138.7	--	--
1983	6394.4	--	--	4262.9	--	--	2131.5	--	--
1984	6511.7	--	--	4341.1	--	--	2170.6	91.55	0.2
1985	6128.6	--	--	4085.8	--	--	2042.9	1166.1	.27
1986	6918.7	--	--	4612.4	--	--	2306.2	1702.8	.32
1987	7143.7	--	--	4762.5	--	--	2381.2	2352.6	.39
1988	7325.6	--	--	4883.8	--	--	2441.9	3081.0	.45
1989	8283.2	--	--	5522.2	--	--	2761.1	3517.8	.45
1990	8628.	--	--	5752.0	--	--	2876.	4258.2	.49
1991	8283.2	--	--	5522.2	--	--	2761.1	5476.2	.56
1992	8489.1	--	--	5659.4	--	--	2829.7	6449.5	.59
1993	8307.2	--	--	5538.1	2949.6	.31	2769.1	7582.6	.64
1994	8283.2	--	--	5522.2	5899.5	.45	2761.1	8660.6	.67
1995	7895.4	--	--	5263.6	7270.3	.52	2631.8	9902.1	.71
1996	7691.9	--	--	5127.9	8485.1	.56	2564.	11049.1	.73
1997	7493.2	--	--	4995.5	9644.8	.60	2497.7	12142.6	.76
1998	7062.3	--	--	4708.2	10978.1	.64	2354.1	13332.2	.78
1999	6777.4	8679.9	.53	4518.3	12176.7	.67	2257.1	14435.8	.80
2000	6573.9	11046.5	.59	4382.6	13237.8	.70	2191.3	15429.1	.82

On-site and off-site storage capacity needs are determined under the constraint that all individual reactor storage pools will conserve their full core discharge capability. The requirement for full core discharge ability at all times constitutes the basis for storage expansion planning, which in itself is a pivotal decision. As was discussed previously, a full core discharge ability may be needed if contigencies leading to a requirement for reactor core inspection or the others leading to full core discharge would occur. The model considers an individual reactor pool as full when the amount of stored spent fuel reaches the pool's capacity in excess of FCR. Further spent fuel discharges then constitute a net requirement for additional storage. The sum of the areas under the curves representing on-site and off-site storage capacity additions over time is therefore equal to the area under the curve representing storage requirements reduced by spent-fuel storage capacity in excess of FCR associated with new reactors. It should be noted also that spent-fuel storage capacity expansion programs, which determine storage capacity expansion over time in an aggregate form, imply the possibility of spent-fuel shuffling between units at the same site (multi-reactor sites) and also between different sites.

The spent-fuel storage capacity installation costs associated with the optimal capacity expansion programs for different storage capacity expansion constraints are displayed in Table 7.1 and Figures 7.8-7.13. Table 7.2 and Figures 7.14-7.18 show the on- and off-site storage costs under the optimal storage capacity expansion

Table 7.2. On-Site and Off-Site Storage Capacity Installation Costs - Zero Demand Case

Year	Costs, $\$10^6$					
	M = ∞		M = 4		M = 3	
	c_1	c_2	c_1	c_2	c_1	c_2
1976	--	--	--	--	--	--
1977	2.74	--	2.74	--	3.86	--
1978	7.02	--	7.02	--	6.77	--
1979	8.18	--	8.18	--	7.34	--
1980	6.05	--	6.05	--	6.05	--
1981	5.67	--	5.67	--	5.67	--
1982	8.51	--	8.51	--	8.51	--
1983	9.16	--	9.16	--	9.16	--
1984	12.06	--	12.06	--	12.06	--
1985	13.63	--	13.63	--	28.28	--
1986	16.41	--	16.41	--	37.75	--
1987	18.67	--	18.67	--	37.56	--
1988	20.99	--	21.0	--	37.12	--
1989	22.99	--	23.0	--	40.44	--
1990	25.17	--	25.17	--	40.59	--
1991	25.5	--	25.50	--	34.19	--
1992	27.16	--	27.16	--	33.13	--
1993	28.65	--	28.65	--	30.65	--
1994	29.88	--	37.83	--	28.90	--
1995	31.01	--	39.06	--	26.04	--
1996	31.84	--	35.98	--	23.99	--
1997	32.37	--	33.14	--	22.09	--
1998	32.79	--	29.53	--	19.69	--
1999	33.17	--	26.79	--	17.86	--
2000	32.76	--	24.57	--	16.38	--
Total	482.4	--	485.5	--	534.1	2.6

Legends: c_1 - On-site unit installation costs
c_2 - Off-site unit installation costs

Table 7.2 (Continued). On-Site and Off-Site Storage Capacity Installation Costs - Zero Demand Case.

Year	Costs, $\$10^6$					
	M = 2.5		M = 2		M = 1.5	
	c_1	c_2	c_1	c_2	c_1	c_2
1976	8.08	--	5.39	--	2.69	--
1977	8.88	--	5.92	--	2.96	--
1978	5.08	--	3.38	--	1.69	--
1979	5.51	--	3.67	--	1.84	17.56
1980	22.4	--	14.93	--	7.47	--
1981	27.71	--	18.47	--	9.24	--
1982	16.21	--	10.81	--	5.4	--
1983	29.24	--	19.50	--	9.75	--
1984	28.70	--	19.13	--	9.57	1.47
1985	26.03	--	17.35	--	8.68	18.01
1986	28.31	--	18.88	--	9.44	25.34
1987	28.17	--	18.78	--	9.39	33.74
1988	27.84	--	18.56	--	9.28	42.57
1989	30.33	--	20.22	--	10.11	46.84
1990	30.44	--	20.29	--	10.15	54.63
1991	25.64	--	17.10	--	8.55	61.65
1992	24.85	--	16.57	--	8.28	68.65
1993	23.00	--	15.33	29.68	7.66	76.31
1994	21.67	--	14.45	56.13	7.22	82.40
1995	19.53	--	13.02	65.4	6.51	89.07
1996	18.00	--	12.00	72.16	6.00	93.97
1997	16.57	--	11.05	77.55	5.52	97.64
1998	14.76	--	9.84	83.46	4.92	101.4
1999	13.40	62.39	8.93	87.52	4.47	103.8
2000	12.29	75.07	8.19	89.96	4.1	104.8
Total	572.6	137.5	341.8	561.9	170.9	1120.0

Table 7.3. On-Site and Off-Site Spent Fuel Storage Costs - Zero Demand Case.

Year	Costs, $\$10^6$							
	M = ∞, 4, 3		M = 2.5		M = 2		M = 1.5	
	c_5	c_6	c_5	c_6	c_5	c_6	c_5	c_6
1976	3.06	--	3.06	--	3.0	--	3.06	--
1977	6.84	--	6.84	--	6.84	--	6.84	--
1978	11.8	--	11.8	--	11.8	--	10.20	4.56
1979	17.46	--	17.46	--	17.46	--	11.85	16.02
1980	23.71	--	23.71	--	23.71	--	18.20	15.73
1981	29.82	--	29.82	--	29.82	--	24.50	15.16
1982	36.11	--	36.11	--	36.11	--	31.00	14.61
1983	44.17	--	44.17	--	44.17	--	39.25	14.08
1984	53.72	--	53.72	--	53.72	--	48.72	14.3
1985	63.6	--	63.6	--	63.6	--	55.62	22.78
1986	75.16	--	75.16	--	75.16	--	63.034	34.62
1987	87.71	--	87.71	--	87.71	--	70.14	50.23
1988	101.3	--	101.3	--	101.3	--	76.86	69.69
1989	115.9	--	115.9	--	115.9	--	84.18	90.6
1990	131.4	--	131.4	--	131.4	--	91.27	114.6
1991	134.6	--	134.6	--	134.6	--	88.62	131.4
1992	147.6	--	147.6	--	147.6	--	92.07	158.5
1993	160.5	--	160.5	--	154.	18.69	94.71	188
1994	173.4	--	173.4	--	159.5	45.74	96.77	219.
1995	186.1	--	186.1	--	160.6	75.94	98.00	251.6
1996	198.3	--	198.3	--	160.9	107.9	98.65	284.8
1997	210.1	--	210.1	--	160.1	140.9	98.79	318.1
1998	221.3	--	221.3	--	158.1	174.8	98.33	351.4
1999	231.9	--	220.	33.94	158.7	209.	97.43	384.2
2000	(240.8) 241.7	(2.6) --	217.3	69.62	156.8	242.0	96.21	415.6
Total	(2706.) 2707.0	(2.61) --	267.1	103.6	2352.	1016.0	1594.	3180.0

Legend: c_5 = On-site storage costs
c_6 = Off-site storage costs
Numbers within parentheses refer to M = 3

plans. Using the present worth concept with an annual discount rate of 10%, all costs are in 1976 dollars.

From the analysis of the zero demand case solutions, important trends are identified. A pivotal case worth studying is a hypothetical situation assuming unrestricted expansion of on- and off-site storage facilities. This assumption eliminates the distinction between whether new storage capacity should be added to new plants or to the existing ones. The solution indicates that off-site storage expansion is not economically attractive. In fact, while on-site capacity is allocated in increasingly large quantities, available initial off-site capacity is left unused. Thus, the costs of transporting and handling the spent fuel are avoided when reprocessing or disposal are not available. The results indicate that gradual additional on-site storage capacity is needed starting in 1977 with about 500 MT and reaching a local maximum in 1979 of 1580 MT. Then, the need gradually increases from an additional 100 MT in 1981 to about 17600 MT in year 2000. Installation costs in 1977 reach about $8 million (1976 dollars) and at the end of this century are $33 million. The cumulative total installation costs under this scenario would amount to about $0.5 million dollars and the spent-fuel storage expenses are $2.7 billion dollars. Observe that for the storage capacity expansion program unrestricted by technological considerations, the optimal installation program follows spent-fuel storage needs determined by the amount of discharged fuel over time which in turn is dependent upon the growth of nuclear power capacity.

The results also indicate a different optimal plan for storage capacity expansion over time if there is a limitation on the on-site capacity expansion. The optimal strategy is then determined by an evaluation of the trade-offs between installation of an on-site storage facility at a particular point in time with the capacity exceeding the current storage needs and the installation of off-site storage facilities with the associated transfer of spent fuel from the reactors to those facilities.

An important result is the optimal plan for capacity expansion assuming installation of high-capacity racks in the new plants, which would increase the standard capacity by a factor of three. It was found that cumulative additional on-site storage of about 10500 MT would be needed to cover spent-fuel storage requirements from 1977 to 1985. This storage capacity could be installed over this period following the storage needs on a year by year basis. Starting with 1985, the optimal plan calls for installation of high-capacity racks at all new plants up to the end of the planning horizon. This policy results in over building on-site storage capacity during 1985 to 1991 by about 19600 MT which would be gradually used up in the following decade. The optimal plan also indicates use of the initial off-site capacity (360 MT) at the end of the planning horizon. The total installation costs in present worth terms are 534 million dollars which represent an increase of about 10% over the costs for unrestricted expansion. The effect of overbuilding the on-site capacity above the current storage needs for the capacity expansion restricted cases is still further accentuated by the increasing limitation for on-site expansion. Compensation for on-site storage capability occurs by installation of more expensive commercial off-site facilities. Under the present worth cost estimates, the optimal plan delays the installation of the off-site storage facilities and postpones their use as long as possible. For example, the limitation of on-site storage capability to the expansion by 100% of storage pools at new plants would result in a need for an off-site capacity of about 3000 MT in 1993 with subsequent gradual additions reaching a cumulative capacity of about 70650 MT in year 2000. The installation costs for this plan are about $900 million which represents an increase of 86% over the case for unconstrained on-site capacity expansion. These results indicate the expansion of the on-site storage capacity associated with the base nuclear capacity extant at the beginning of the planning horizon (1976) (total capacity 45,000 MWe) even though these reactors have partially filled storage basins. A hypothetical situation was studied in which in addition to the capacity expansion by 200% associated with the new plants also capacity of the storage pools belonging to reactors existing at the beginning could be expanded by a factor of three at rate of 10% per year over the period 1977-1986. It was found that the capacity additions during 1977 to 1985 would not be used by the optimal plan, but the additions starting in 1986 would. The above cited results indicate the emphasis on the spent fuel storage capacity plan as a time-decision-action phased series of events.

7.2 Pessimistic Reprocessing Scenario

The pessimistic reprocessing forecast assumes start-up of the reprocessing activity in mid-1983. The schedule for reprocessing capacity additions is shown in Table 6.4. The spent-fuel storage requirements under this alternative are displayed in Table 6.3. The optimal capacity expansion program for this scenario is exhibited in Table 7.4 and Figures 7.19 through 7.23.

It is of interest to investigate features of the optimal capacity expansion program under this demand scenario in view of the results for the zero demand case. In both plans, the cases with unconstrained on-site capacity expansion will be compared. As can be expected, reprocessing of spent fuel significantly will reduce the pressure for storage capacity expansion. The start-up of reprocessing in 1983 results in a reduction of the on-site storage capacity needs around 1985 by about 1000 MT. During the period 1985 to 1995, the cumulative storage capacity requirements are reduced from about 83000 MT for the zero demand case to about 40000 MT. This represents a decrease of about 110%.

The variation of the capacity installation costs and spent fuel storage costs over time are shown in Tables 7.5, 7.6, and Figures 7.25-7.32. Compared with the zero demand case, the total capacity installation costs over the planning horizon are reduced to about 380 million dollars, which amounts to a reduction by 43%.

Table 7.4. Solutions - Pessimistic Reprocessing Scenario

Year	M = ∞			M = 3			M = 2.5		
	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction
1976	--	--	--	--	--	--	--	--	--
1977	506.6	--	--	715.3	--	--	1387.2	--	--
1978	1324.1	--	--	1276.8	--	--	957.6	--	--
1979	1572.2	--	--	1410.9	--	--	1058.1	--	--
1980	1183.2	--	--	1183.2	--	--	1183.2	--	--
1981	1151.4	--	--	1151.4	--	--	1151.4	--	--
1982	1794.1	--	--	1794.1	--	--	1794.1	--	--
1983	1627.6	--	--	1627.6	--	--	1627.6	--	--
1984	1612.5	--	--	1612.5	--	--	1612.5	--	--
1985	1333.9	--	--	1333.9	--	--	1333.9	--	--
1986	1759.1	--	--	1759.1	--	--	1759.1	--	--
1987	2483.8	--	--	2483.8	--	--	2483.8	--	--
1988	3272.8	--	--	3272.8	--	--	3272.8	--	--
1989	3278.8	--	--	3278.8	--	--	2278.8	--	--
1990	3134.2	--	--	3134.2	--	--	3134.2	--	--
1991	3487.2	--	--	3487.2	--	--	4250.	--	--
1992	3539.2	--	--	3539.2	--	--	8489.1	--	--
1993	4601.7	--	--	4601.7	--	--	8307.2	--	--
1994	5671.6	--	--	5671.6	--	--	8283.2	--	--
1995	6783.9	--	--	8059.	--	--	7895.4	--	--
1996	7863.1	--	--	10255.9	--	--	7691.9	--	--
1997	8890.3	--	--	9991.	--	--	7493.2	--	--
1998	9936.3	--	--	9416.4	--	--	7062.3	--	--
1999	10945.	--	--	9036.6	--	--	6777.4	--	--
2000	11870.4	--	--	8765.2	--	0.06	6573.9	--	0.06

Table 7.4 (Continued). Solutions - Pessimistic Reprocessing Scenario

Year	M = 2			M = 1.5		
	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction
1976	962.7	--	--	490.	--	--
1977	1096.5	--	--	548.2	--	--
1978	638.4	--	--	319.2	--	.3142
1979	705.4	--	--	352.7	927.7	.69
1980	1183.2	--	--	1461.1	--	--
1981	2533.9	--	--	1875.9	--	--
1982	2277.5	--	--	1138.7	--	--
1983	4262.9	--	--	2131.5	--	--
1984	4341.1	--	--	2170.6	--	--
1985	4085.8	--	--	2042.9	--	--
1986	4612.4	--	--	2306.2	--	--
1987	4762.5	--	--	2381.2	--	--
1988	4883.8	--	--	2441.9	--	--
1989	5522.2	--	--	2761.1	--	--
1990	5752.	--	--	2876.	--	--
1991	5522.2	--	--	2761.1	--	--
1992	5659.4	--	--	2829.7	480.6	.09
1993	5538.1	--	--	2769.1	1832.6	.29
1994	5522.2	--	--	2761.1	2910.6	.40
1995	5263.6	--	--	2631.8	4152.1	.50
1996	5127.9	--	--	2564.	5299.1	.57
1997	4995.5	--	--	2497.7	6392.6	.62
1998	4708.2	--	--	2354.1	7582.2	.67
1999	4578.3	--	--	2259.1	8685.8	.71
2000	4382.6	--	0.06	2191.3	9679.11	.74

Table 7.5. On- and Off-Site Storage Capacity Installation Costs - Pessimistic Reprocessing Scenario

Year	Costs, $\$10^6$									
	M = ∞		M = 3		M = 2.5		M = 2		M = 1.5	
	c_1	c_2	c_1	c_2	c_1	c_2	c_1	c_2	c_1	c_2
1976	--	--	--	--	--	--	5.29	--	2.69	--
1977	2.74	--	3.86	--	7.49	--	5.92	--	2.96	--
1978	7.02	--	6.77	--	5.08	--	3.38	--	1.69	--
1979	8.18	--	7.34	--	5.51	--	3.67	--	1.84	17.56
1980	6.05	--	6.05	--	6.05	--	6.05	--	7.47	--
1981	5.67	--	5.67	--	5.67	--	12.48	--	9.24	--
1982	8.51	--	8.51	--	8.51	--	10.81	--	5.4	--
1983	7.44	--	7.44	--	7.44	--	19.5	--	9.75	--
1984	7.11	--	7.11	--	7.11	--	19.13	--	9.57	--
1985	5.66	--	5.66	--	5.66	--	17.35	--	8.67	--
1986	7.2	--	7.2	--	7.2	--	18.87	--	9.44	--
1987	9.79	--	9.79	--	9.79	--	18.78	--	9.39	--
1988	12.44	--	12.44	--	12.44	--	18.55	--	9.28	--
1989	12.01	--	12.01	--	12.01	--	20.22	--	10.11	--
1990	11.06	--	11.06	--	11.06	--	20.3	--	10.15	--
1991	10.8	--	10.8	--	13.16	--	17.1	--	8.54	--
1992	10.36	--	10.36	--	24.85	--	16.57	--	8.28	51.15
1993	12.73	--	12.73	--	22.99	--	15.33	--	7.66	18.44
1994	14.84	--	14.84	--	21.67	--	14.45	--	7.22	27.69
1995	16.78	--	19.94	--	19.53	--	13.02	--	6.51	37.35
1996	18.39	--	23.99	--	17.99	--	11.99	--	6.	45.07
1997	19.66	--	22.09	--	16.57	--	11.05	--	5.52	51.40
1998	20.77	--	19.69	--	14.76	--	9.84	--	4.92	51.64
1999	21.63	--	17.86	--	13.4	--	8.93	--	4.47	62.43
2000	22.18	--	16.38	--	12.29	--	8.19	--	4.1	65.77
Total	279.0	--	279.6	--	288.2	--	326.8	--	170.9	388.5

Table 7.6. On-Site and Off-Site Spent-Fuel Storage Costs - Pessimistic Reprocessing Scenario

Year	Costs, $\$10^6$			
	M = ∞, 3, 2.5, 2		M = 1.5	
	c_5	c_6	c_5	c_6
1976	3.06	--	3.06	--
1977	6.84	--	6.84	--
1978	11.80	--	10.21	4.56
1979	17.46	--	11.86	16.02
1980	23.71	--	18.20	15.7
1981	29.81	--	24.51	15.16
1982	36.11	--	31.	14.61
1983	43.10	--	38.16	14.08
1984	49.52	--	44.77	13.56
1985	54.48	--	49.9	13.07
1986	60.51	--	56.1	12.6
1987	67.95	--	63.71	12.14
1988	76.77	--	72.68	11.7
1989	85.3	--	81.35	11.27
1990	92.92	--	89.12	10.86
1991	91.51	--	88.17	9.53
1992	96.12	--	92.07	11.57
1993	101.8	--	94.71	20.16
1994	108.3	--	96.77	32.9
1995	115.4	--	98.	49.78
1996	123.	--	98.65	69.6
1997	130.8	--	98.79	91.51
1998	138.7	--	98.33	115.3
1999	146.5	--	97.43	140.3
2000	154.1 (153.2)	0.0 (2.6)	96.21	165.5
Total	1866.0 (1.865)	0.0 (2.6)	1561.0	871.5

Legend: Values in the parentheses are for M = 2

The total reduction in the spent-fuel storage costs is very significant. It represents savings of 840 million dollars compared with the zero demand case. The total storage costs amount to about 1.9 billion dollars.

The effect of the constraints on on-site capacity expansion is similar to that observed with the zero demand case. If the capacity of the storage pools associated with the new plants could be increased by 200%, the optimal plan for on-site capacity installation would be identical to that of the unconstrained case for the period from the beginning of the planning horizon up to the year 1995. In that year, the on-site storage addition would amount to about 1200 MT over the current storage need. Starting with 1996 the on-site storage capacity, according to the optimal program, should expand three times. The initial unused off-site storage capability (360 MT) with an additional 405 MT installed during 1976 to 1977 is used up in year 2000 when about 6% of the spent fuel discharged in that year should be transported to the off-site storage facilities. The phenomenon of the on-site capacity overbuilding is gradually shifted towards the beginning of the planning horizon with a decreasing upper limit on the on-site storage capacity expansion. For example, if the on-site storage capacity of new plants could expand by only 100%, overbuilding then would have to start in 1982 when all new plants since that year should have their capacity expanded two times. This measure would still obviate the necessity of installing the off-site storage pools. The excess on-site capacity built during the period

1981 to 1992 would be used up gradually during the remaining years of the planning horizon. The limitation of the on-site capacity expansion to 50% would require that an off-site storage facility of capacity about 1000 MT be ready in 1979. During that year, about 30% and the following year about 68% of discharged fuel must be transported off-site under the optimal plan. Additional off-site storage capacity would not be necessary until 1992. After that year, the optimal program requires gradually increasing off-site off-site storage capability, reaching a cummulative of about 47000 MT in the year 2000. Total capacity installation and spent-fuel storage costs for this program would require an increase of 40% with a $2.15 billion dollars in expenditures associated with the program and possibility of expanding the standard design capacity of the reactor pools by 200%.

7.3 Realistic Reprocessing Scenario

In the realistic reprocessing forecast, it is assumed that the reprocessing activity will start-up again in mid-1981.[10] The timing of the spent fuel storage requirements under this scenario is exhibited in Table 6.3 and Figure 6.1. The solutions indicating the optimal timing of the on-site and off-site storage capacity additions are displayed in Table 7.7 and Figures 7.33-7.38. Tables 7.8, 7.9, and Figures 7.39-7.45 show the expenditures associated with the optimal plans under several situations simulating the on-site capacity expansion restrictions.

Table 7.7. Solutions - Realistic Reprocessing Scenario

Year	M = ∞			M = 3			M = 2.5		
	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction
1976	--	--	--	--	--	--	--	--	--
1977	506.6	--	--	715.3	--	--	1387.2	--	--
1978	1324.1	--	--	1276.8	--	--	957.6	--	--
1979	1572.2	--	--	1410.9	--	--	1058.1	--	--
1980	1183.2	--	--	1183.2	--	--	1183.2	--	--
1981	776.4	--	--	776.4	--	--	776.4	--	--
1982	669.1	--	--	669.1	--	--	669.1	--	--
1983	127.6	--	--	127.6	--	--	127.6	--	--
1984	487.5	--	--	487.5	--	--	487.5	--	--
1985	958.9	--	--	958.9	--	--	959.0	--	--
1986	1759.1	--	--	1759.1	--	--	1759.1	--	--
1987	1733.8	--	--	1733.8	--	--	1333.8	--	--
1988	1522.8	--	--	1522.8	--	--	1522.8	--	--
1989	1528.8	--	--	1528.8	--	--	1528.8	--	--
1990	1384.2	--	--	1384.2	--	--	1384.2	--	--
1991	2487.2	--	--	2487.2	--	--	3240.	--	--
1992	3529.2	--	--	3529.2	--	--	8489.1	--	--
1993	4601.7	--	--	4601.7	--	--	8307.2	--	--
1994	5671.6	--	--	5671.6	--	--	8283.2	--	--
1995	6783.9	--	--	8059.	--	--	7895.4	--	--
1996	7863.1	--	--	10255.9	--	--	7691.9	--	--
1997	8890.3	--	--	9991.	--	--	7493.2	--	--
1998	9936.3	--	--	9416.4	--	--	7062.3	--	--
1999	10945.0	--	--	9036.5	--	--	6777.4	--	--
2000	11870.4	--	--	8765.2	--	0.06	6573.9	--	0.06

Table 7.7 (Continued). Solutions - Realistic Reprocessing Scenario

Year	M = 2			M = 1.5		
	x_1 [MT]	x_2 [MT]	x_3 [MT]	x_1 [MT]	x_2 [MT]	x_3 [MT]
1976	962.7	--	--	490.	--	--
1977	1096.5	--	--	548.2	--	--
1978	638.4	--	--	319.2	--	.31
1979	705.4	--	--	352.7	927.9	.69
1980	1183.2	--	--	1461.1	--	--
1981	776.4	--	--	1875.3	--	--
1982	669.1	--	--	1138.7	--	--
1983	127.6	--	--	2131.5	--	--
1984	487.5	--	--	2170.6	--	--
1985	3930.6	--	--	2042.9	--	--
1986	4612.4	--	--	2306.2	--	--
1987	4762.5	--	--	2381.2	--	--
1988	4883.8	--	--	2441.9	--	--
1989	5522.2	--	--	2761.1	--	--
1990	5752.	--	--	2876.	--	--
1991	5522.2	--	--	2761.1	--	--
1992	5659.4	--	--	2829.7	--	--
1993	5538.1	--	--	2769.1	--	--
1994	5522.2	--	--	2761.1	--	--
1995	5263.6	--	--	2631.8	--	--
1996	5127.9	--	--	2564.	3165.	.34
1997	4995.5	--	--	2497.7	6392.6	.62
1998	4708.2	--	--	2354.1	7582.2	.67
1999	4518.3	--	--	2259.1	8685.8	.71
2000	4382.6	--	0.06	2191.3	9679.1	.74

Table 7.8. On-Site and Off-Site Storage Capacity Installation Costs - Realistic Reprocessing Scenario

Year	Costs, $\$10^6$									
	M = ∞		M = 3		M = 2.5		M = 2		M = 1.5	
	c_1	c_2	c_1	c_2	c_1	c_2	c_1	c_2	c_1	c_2
1976	--	--	--	--	--	--	5.29	--	2.69	--
1977	2.74	--	3.86	--	7.49	--	5.92	--	2.96	--
1978	7.02	--	6.77	--	5.08	--	3.38	--	1.69	--
1979	8.18	--	7.34	--	5.51	--	3.67	--	1.84	17.56
1980	6.05	--	6.05	--	6.05	--	6.05	--	7.47	--
1981	3.82	--	3.82	--	3.82	--	3.82	--	9.24	--
1982	3.18	--	3.18	--	3.18	--	3.18	--	5.40	--
1983	.58	--	5.84	--	.58	--	.58	--	9.75	--
1984	2.15	--	2.15	--	2.15	--	2.15	--	9.57	--
1985	4.07	--	4.07	--	4.67	--	16.69	--	8.68	--
1986	7.2	--	7.2	--	7.2	--	18.88	--	9.44	--
1987	6.84	--	6.84	--	6.84	--	18.78	--	9.39	--
1988	5.79	--	5.79	--	5.79	--	18.56	--	9.28	--
1989	5.6	--	5.6	--	5.6	--	20.22	--	10.11	--
1990	4.88	--	4.88	--	4.88	--	20.3	--	10.15	--
1991	7.7	--	7.7	--	10.03	--	17.1	--	8.55	--
1992	10.33	--	10.33	--	24.85	--	16.57	--	8.28	--
1993	12.73	--	12.73	--	23.	--	15.33	--	7.66	--
1994	14.84	--	14.84	--	21.67	--	14.45	--	7.22	--
1995	16.78	--	19.94	--	19.53	--	13.02	--	6.51	--
1996	18.39	--	23.99	--	18.	--	12.00	--	6.00	26.92
1997	19.66	--	22.09	--	16.57	--	11.05	--	5.52	51.4
1998	20.77	--	19.69	--	14.76	--	9.84	--	4.92	57.64
1999	21.63	--	17.86	--	13.4	--	8.93	--	4.47	62.43
2000	22.18	--	16.38	--	12.29	--	8.19	--	4.10	65.77
Total	233.1	--	233.7	--	242.3	--	273.9	--	170.9	281.7

Table 7.9. On-Site and Off-Site Spent-Fuel Storage Costs - Realistic Reprocessing Scenario

Year	Costs, $\$10^6$			
	M = ∞, 3, 2.5, (2)		M = 1.5	
	c_5	c_6	c_5	c_6
1976	3.06	--	3.06	--
1977	6.84	--	6.84	--
1978	11.8	--	10.21	4.56
1979	17.46	--	11.86	16.02
1980	23.71	--	18.2	15.73
1981	28.64	--	23.33	15.16
1982	31.58	--	26.47	14.61
1983	34.35	--	29.42	14.08
1984	37.94	--	33.2	13.56
1985	42.31	--	37.74	13.07
1986	48.79	--	44.38	12.5
1987	54.78	--	50.53	12.14
1988	59.84	--	55.75	11.7
1989	64.9	--	60.96	11.27
1990	69.35	--	65.54	10.86
1991	68.85	--	65.51	9.53
1992	74.68	--	71.53	9.01
1993	81.5	--	78.52	8.52
1994	89.12	--	86.30	8.05
1995	97.31	--	94.64	7.6
1996	105.9	--	98.65	20.66
1997	114.6	--	98.79	45.23
1998	123.4	--	98.33	71.58
1999	132.	--	97.43	98.89
2000	140.4 (139.5)	-- (2.6)	96.21	126.4
Total	1563 (1562)	-- (2.6)	13.63	570.8

The start-up of reprocessing in 1981 has a significant effect upon storage capacity needs during 1980's. Reprocessing of spent fuel in that period reduces storage capacity requirements from about 47000 MT in the zero demand case to about 13500 MT. This represents a reduction of 240%. Under this scenario, during the period 1976 to 1990, the discounted on-site capacity installation costs are 68 million dollars and the total spent-fuel storage costs are $535.4 million. During the same period, the profit realized by recycling the recovered uranium and plutonium back in LWR's would amount to 1358.8 million dollars (see Table (8.6), Chapter 8). In terms of 1976 dollars, the net revenue (when only expenditures and revenues of the post-irradiation period are considered) would amount to 755 million dollars. However, during the 1990's, this revenue is reduced by about $27 million dollars due to the fact that the spent-fuel storage expenditures during that decade exceed the profit derived from the recycling of the recovered nuclear fuel. Clearly, additional reprocessing capacity will be required in the early 1990's.

The constraints on the on-site capacity expansion influence the timing of the capacity additions over time. The optimal program indicates that the possibility of expanding spent fuel storage racks of the new plants at least by 100% would not eliminate the need for installation of off-site spent-fuel storage facilities. However, the timing of the overbuilding of on-site storage capacity, in order to provide capacity for spent-fuel discharged later, shifts greater even though the standard reactor pool design capacity can be expanded two or three times. For instance, if reactor pool capacity can be expanded on an average by 100%,the optimal plan indicates the installation of reactor pools of two times the current standard capacity in all nuclear plants coming on line after 1985. On the other hand, if a 200% expansion is feasible, the overbuilding over the current spent fuel storage needs is not indicated until 1995. In fact, during the period 1985-1990,an additional capacity of 9000 MT would be needed, if the storage capability of the reactors to be installed after 1990 would be three times the current standard design capacity. This is compared with the addition of about 30000 MT if the on-site storage capability would be increased by a factor of two. The advanced storage capacity overbuilding results in an increase of the total capacity installation costs of about 15%. The results cited above emphasize a need for careful capacity expansion planning in view of the nuclear capacity growth, spent fuel demand forecast, and technological limitations associated with the spent-fuel storage capacity expansion.

7.4 Optimistic Reprocessing Forecast

The optimistic reprocessing forecast assumes the start-up of reprocessing activity in mid-1979. The reprocessing capacity schedule for this scenario is exhibited in Table 6.4. The resulting spent-fuel storage requirements over time are shown in Table 6.3.

The optimal timing of the storage capacity installation were investigated under several capacity expansion constraining situations. The optimal capacity addition plans are displayed in Table 7.9 and Figures 7.46-7.51. Table 7.11 and Figures 7.52-7.56 display the timing of the capacity installation costs. Spent-fuel storage costs are shown in Table 7.12 and Figures 7.57-7.58.

The results indicate that reinitiation of spent-fuel reprocessing in 1979 obviates the need for spent-fuel storage capacity additions during the years 1981 to 1989. During the period 1976-1980, which precedes the start-up of reprocessing, about 3086 MT of the on-site storage capacity would be needed. However, it should be pointed out that the above capacity installation plan would be feasible if the on-reactor-site storage capacity of new power plants installed after 1990 could be expanded at least by 150%. Also, it can be observed that the on-site capacity expansion restrictions affect the optimal capacity installation plan. The increase of current standard reactor pool capacity (1.4 FCR) by a factor of two would require starting these additions of storage capacity by 1986. During the years 1986 to 1989, the capacity in excess of the current storage needs would amount to about 16000 MT which would be gradually used up during the last decade of this century. Limiting the expansion of reactor pools constructed in the future to only 50% would require addition of the off-site storage facility of about 600 MT capacity in 1979. In 1978 about 30% and in 1979 about 60% of the discharged fuel would have to be transferred off-site and also the initial off-site capacity (~ 400 MT) would be used. In addition, towards year 2000 spent-fuel storage requirements would have to be partially satisfied by off-site facilities of about 24500 MT capacity.

The total on-site capacity installation costs under the optimistic reprocessing alternative would amount to about 185 million dollars. This amount, when compared with 482.5 million for the zero demand case, represents a saving of about 160%. The storage cost saving between the two above cited cases would be about 1.5 billion dollars. Revenues acquired by reprocessing and recycling the recovered nuclear fuel would amount to 3.126 billion dollars. Net savings generated by this reprocessing program, when spent-fuel storage expenses are subtracted, would be about 1.8 billion.

Table 7.10. Solutions - Optimistic Reprocessing Scenario

Year	M = ∞			M = 3			M = 2.5		
	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction	x_1 [MT]	x_2 [MT]	x_3 fraction
1976	--	--	--	--	--	--	--	--	--
1977	506.6	--	--	553.9	--	--	1012.2	--	--
1978	1324.1	--	--	1276.8	--	--	957.6	--	--
1979	1197.2	--	--	1197.2	--	--	1058.1	--	--
1980	58.2	--	--	58.2	--	--	58.2	--	--
1981	--	--	--	--	--	--	--	--	--
1982	--	--	--	--	--	--	--	--	--
1983	--	--	--	--	--	--	--	--	--
1984	--	--	--	--	--	--	--	--	--
1985	--	--	--	--	--	--	--	--	--
1986	--	--	--	--	--	--	--	--	--
1987	--	--	--	--	--	--	--	--	--
1988	--	--	--	--	--	--	--	--	--
1989	--	--	--	--	--	--	--	--	--
1990	948.2	--	--	948.2	--	--	948.2	--	--
1991	2487.2	--	--	2487.2	--	--	3240.0	--	--
1992	3529.2	--	--	3529.2	--	--	8489.1	--	--
1993	4601.7	--	--	4601.7	--	--	8307.2	--	--
1994	5671.6	--	--	5671.6	--	--	8283.2	--	--
1995	6783.9	--	--	8059.0	--	--	7895.4	--	--
1996	7863.1	--	--	10255.9	--	--	7691.4	--	--
1997	8890.3	--	--	9991.0	--	--	7493.2	--	--
1998	9936.3	--	--	9416.4	--	--	7062.3	--	--
1999	10945.	--	--	9036.6	--	--	6777.4	--	--
2000	11870.0	--	--	8765.2	--	0.06	6573.9	--	0.06

Table 7.10 (Continued). Solutions - Optimistic Reprocessing Scenario

Year	M = 2			M = 1.5		
	x_1 [MT]	x_2 [MT]	x_3 [MT]	x_1 [MT]	x_2 [MT]	x_3 [MT]
1976	587.7	--	--	490.	--	--
1977	1096.5	--	--	548.2	--	--
1978	638.4	--	--	319.2	--	.31
1979	705.4	--	--	352.7	552.9	.60
1980	58.2	--	--	1461.1	--	--
1981	--	--	--	1875.3	--	--
1982	--	--	--	1138.7	--	--
1983	--	--	--	2131.5	--	--
1984	--	--	--	2170.6	--	--
1985	--	--	--	2042.9	--	--
1986	603.7	--	--	2306.2	--	--
1987	4762.5	--	--	2381.2	--	--
1988	4883.8	--	--	2441.9	--	--
1989	5522.2	--	--	2761.1	--	--
1990	5752.0	--	--	2876.	--	--
1991	5522.2	--	--	2761.1	--	--
1992	5659.4	--	--	2829.7	--	--
1993	5538.1	--	--	2769.1	--	--
1994	5522.2	--	--	2761.1	--	--
1995	5263.6	--	--	2631.8	--	--
1996	5128.0	--	--	2564.0	--	--
1997	4995.5	--	--	2497.7	--	--
1998	4708.2	--	--	2354.1	6014.8	.53
1999	4518.3	--	--	2259.1	8685.8	.71
2000	4382.6	--	0.06	2191.3	9679.1	.74

Table 7.11. On-Site and Off-Site Storage Capacity Installation Costs - Optimistic Reprocessing Scenario

Year	Costs, $\$10^6$									
	M = ∞		M = 3		M = 2.5		M = 2		M = 1.5	
	c_1	c_2	c_1	c_2	c_1	c_2	c_1	c_2	c_1	c_2
1976	--	--	--	--	--	--	3.23	--	2.69	--
1977	2.73	--	3.00	--	5.47	--	5.92	--	2.96	--
1978	7.02	--	6.77	--	5.08	--	3.38	--	1.69	--
1979	6.23	--	6.23	--	5.51	--	3.67	--	1.84	10.47
1980	0.297	--	.297	--	0.297	--	2.97	--	7.47	--
1981	--	--	--	--	--	--	--	--	9.24	--
1982	--	--	--	--	--	--	--	--	5.4	--
1983	--	--	--	--	--	--	--	--	9.75	--
1984	--	--	--	--	--	--	--	--	9.57	--
1985	--	--	--	--	--	--	--	--	8.68	--
1986	--	--	--	--	--	--	2.47	--	9.44	--
1987	--	--	--	--	--	--	18.78	--	9.39	--
1988	--	--	--	--	--	--	18.55	--	9.28	--
1989	--	--	--	--	--	--	20.22	--	10.11	--
1990	3.35	--	3.34	--	3.35	--	20.29	--	10.15	--
1991	7.7	--	7.7	--	10.03	--	17.09	--	8.55	--
1992	10.33	--	10.33	--	24.85	--	16.56	--	8.28	--
1993	12.73	--	12.73	--	23.00	--	15.33	--	7.66	--
1994	14.83	--	14.83	--	21.67	--	14.45	--	7.22	--
1995	16.78	--	19.94	--	19.53	--	13.02	--	6.51	--
1996	18.39	--	23.99	--	18.00	--	12.00	--	6.00	--
1997	19.66	--	22.09	--	16.57	--	11.05	--	5.52	--
1998	20.77	--	19.69	--	14.76	--	9.84	--	4.92	45.73
1999	21.63	--	17.86	--	13.40	--	8.93	--	4.47	62.43
2000	22.18	--	16.38	--	12.29	--	8.19	--	4.1	65.77
Total	184.7	--	185.2	--	193.8	--	223.3	--	170.9	184.4

Table 7.12. On-Site and Off-Site Spent-Fuel Storage Costs - Optimistic Reprocessing Scenario

Year	Costs, $\$10^6$			
	M = ∞, 3, 2.5, (2)		M = 1.5	
	c_5	c_6	c_5	c_6
1976	3.06	--	3.06	--
1977	6.84	--	6.84	--
1978	11.8	--	10.20	4.56
1979	16.22	--	11.86	12.47
1980	18.83	--	14.55	12.25
1981	19.24	--	15.11	11.8
1982	19.13	--	15.15	11.37
1983	21.56	--	17.42	10.96
1984	25.33	--	21.63	10.56
1985	28.13	--	24.57	10.18
1986	30.56	--	27.13	9.81
1987	32.02	--	29.51	9.4
1988	34.45	--	31.29	9.11
1989	38.11	--	35.04	8.77
1990	43.52	--	40.56	8.46
1991	46.19	--	43.6	7.42
1992	53.26	--	50.8	7.01
1993	61.24	--	58.92	6.63
1994	69.97	--	67.78	6.27
1995	79.2	--	77.13	5.93
1996	88.77	--	86.81	5.6
1997	98.44	--	96.59	5.3
1998	108.1	--	98.33	27.87
1999	117.6	--	97.43	57.6
2000	126.8 (125.9)	-- (2.6)	96.21	87.3
Total	1200 1198	-- (2.6)	1077.	346.7

7.5 Graphical Display of the Results

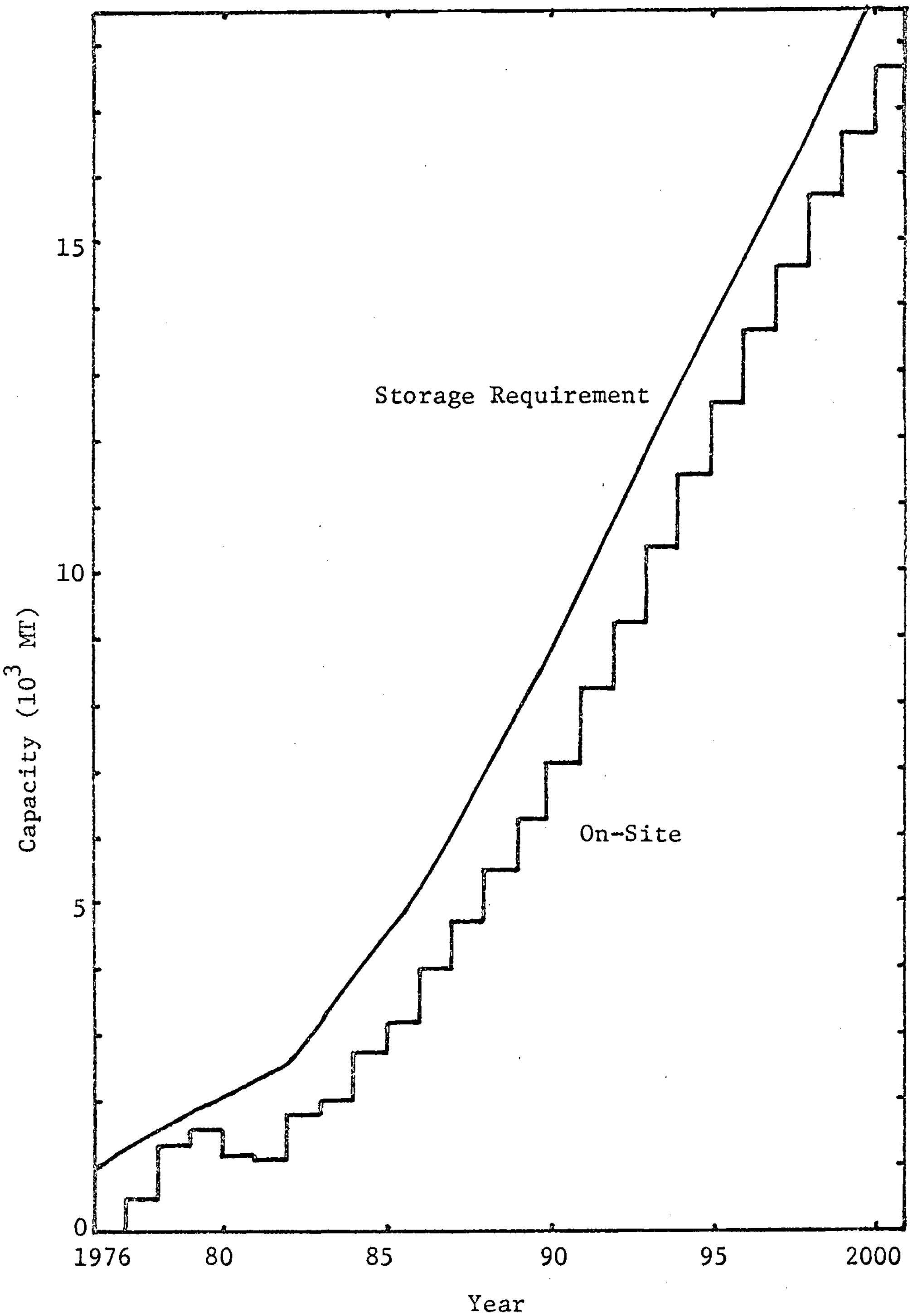


Figure 7.1. On-Site and Off-Site Storage Capacity Growth
- Zero Demand, Unconstrained Case.

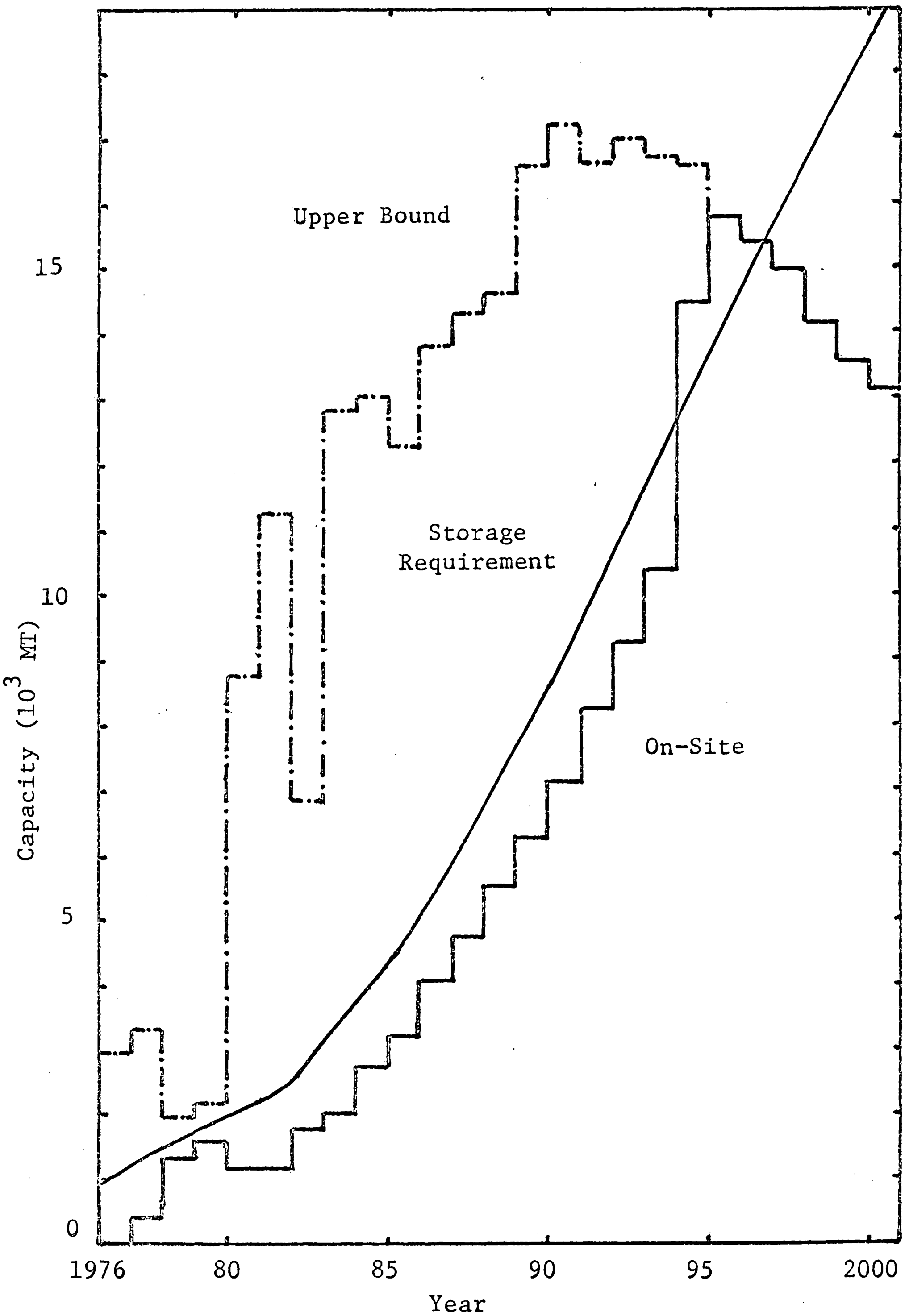


Figure 7.2. On-Site and Off-Site Storage Capacity Growth - Zero Demand, M = 4.

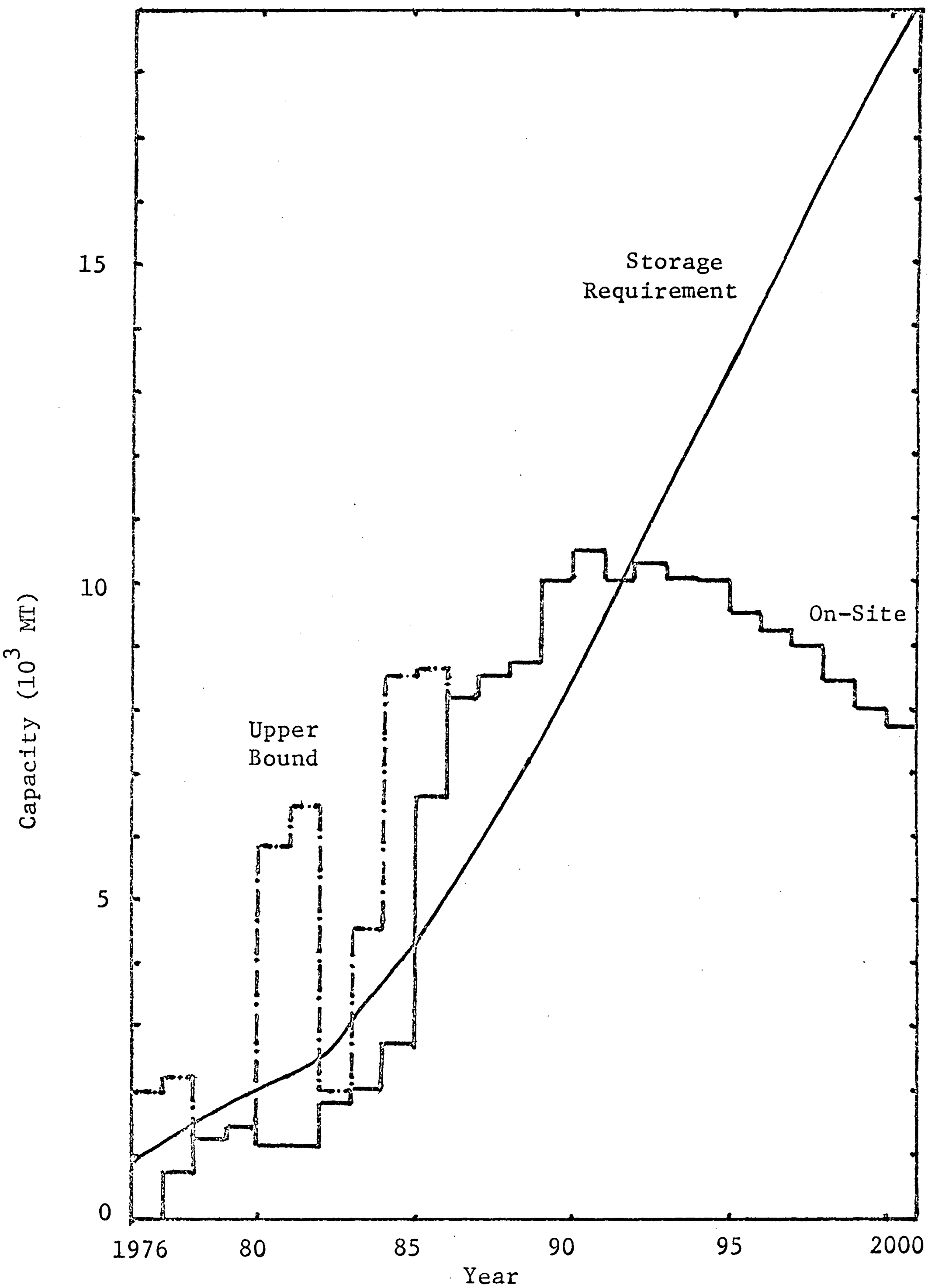


Figure 7.3. On-Site and Off-Site Storage Capacity Growth - Zero Demand, M = 3.

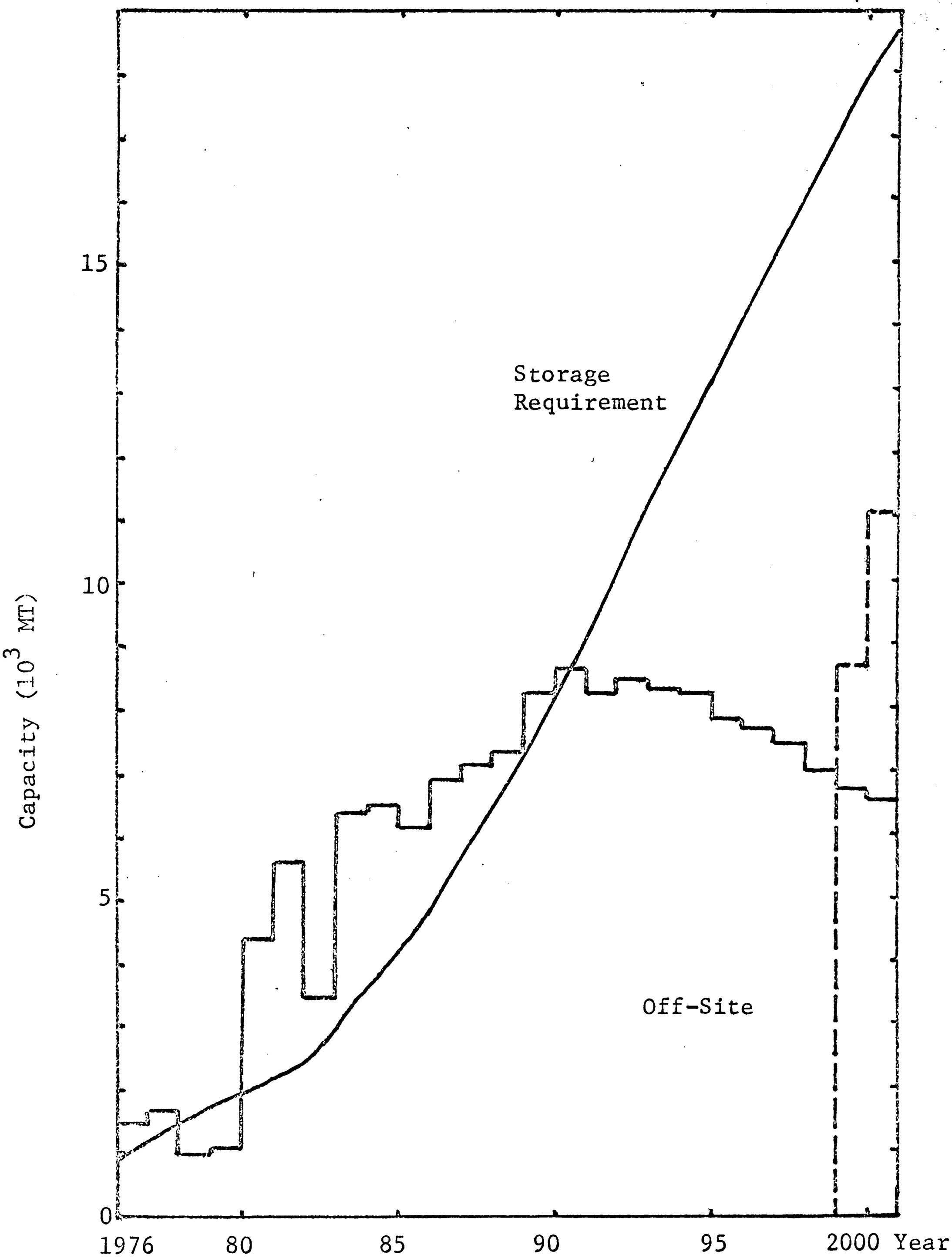


Figure 7.4. On-Site and Off-Site Storage Capacity Growth - Zero Demand, M = 2.5.

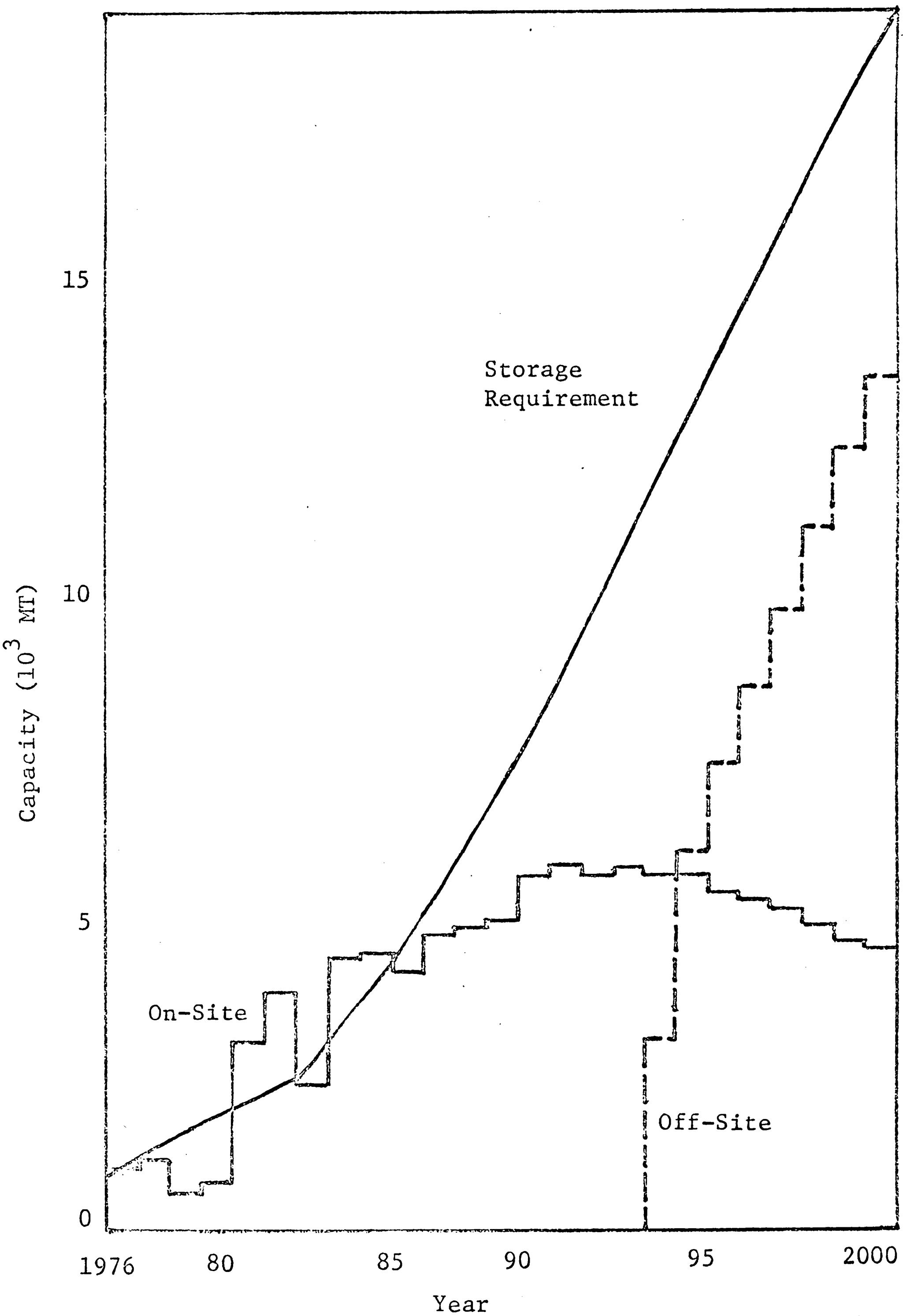


Figure 7.5. On-Site and Off-Site Storage Capacity Growth
- Zero Demand, M = 2.

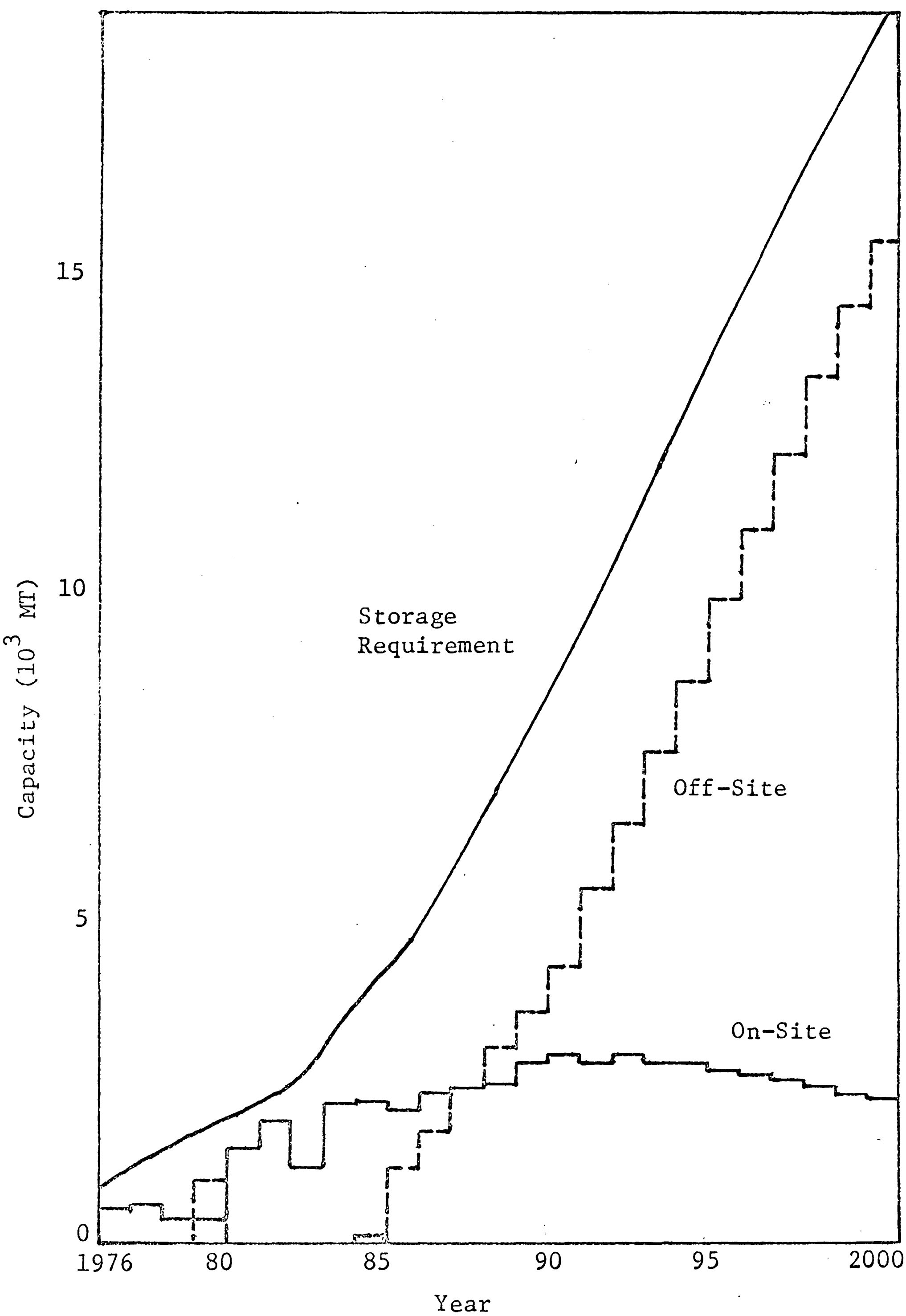


Figure 7.6. On-Site and Off-Site Storage Capacity Growth - Zero Demand, M = 1.5.

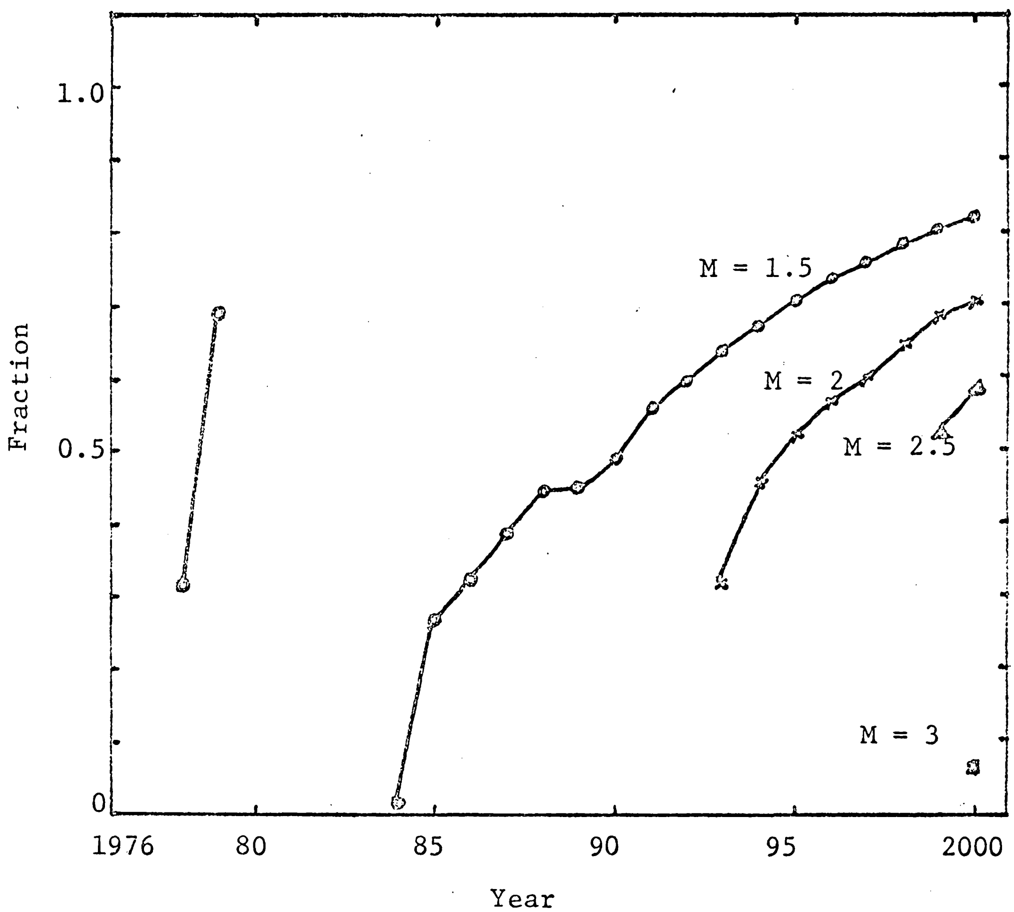


Figure 7.7. Fraction of Spent Fuel Transferred Off-Site - Zero Demand.

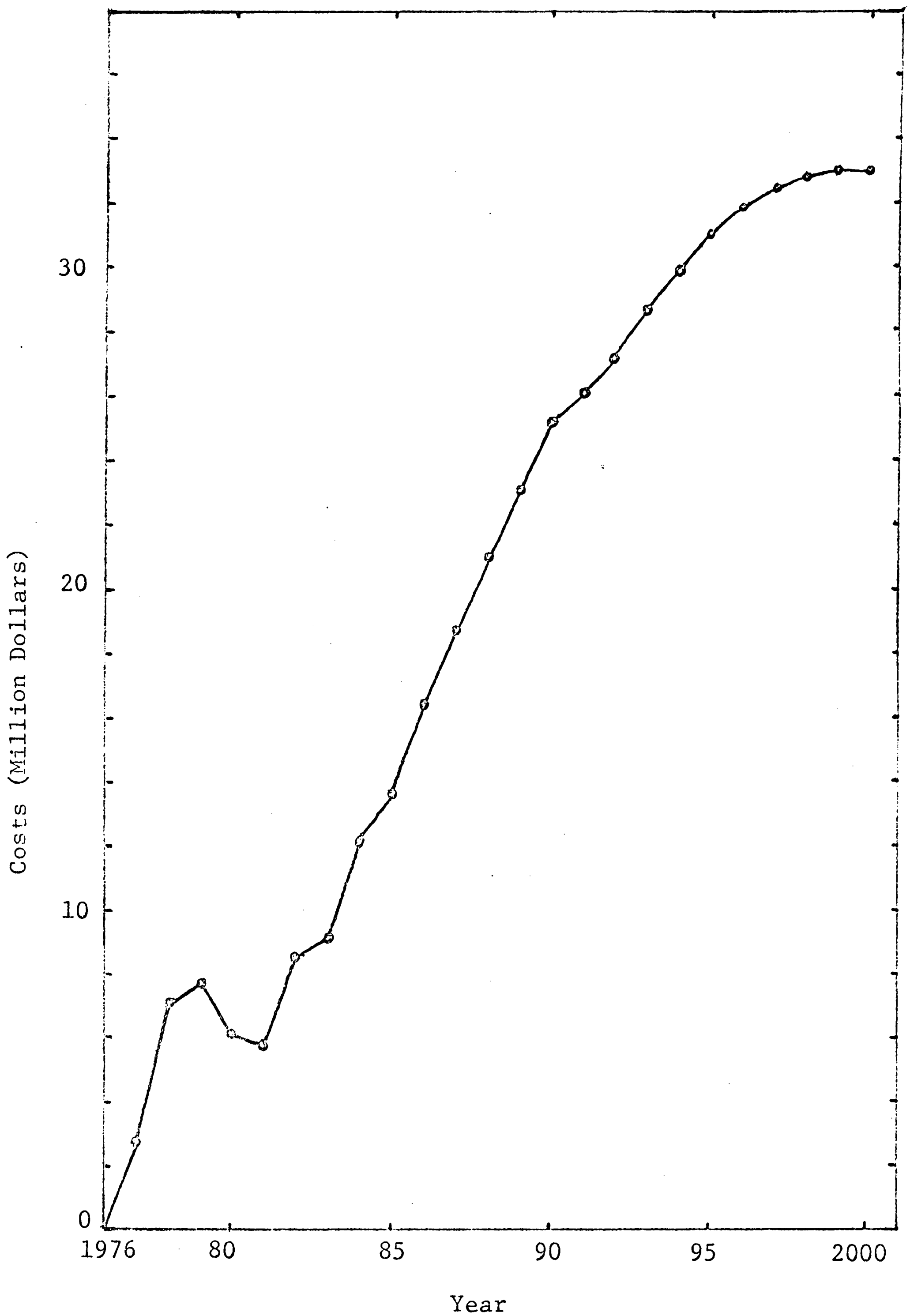


Figure 7.8. On-Site Storage Capacity Installation Costs - Zero Demand, Unconstrained Case.

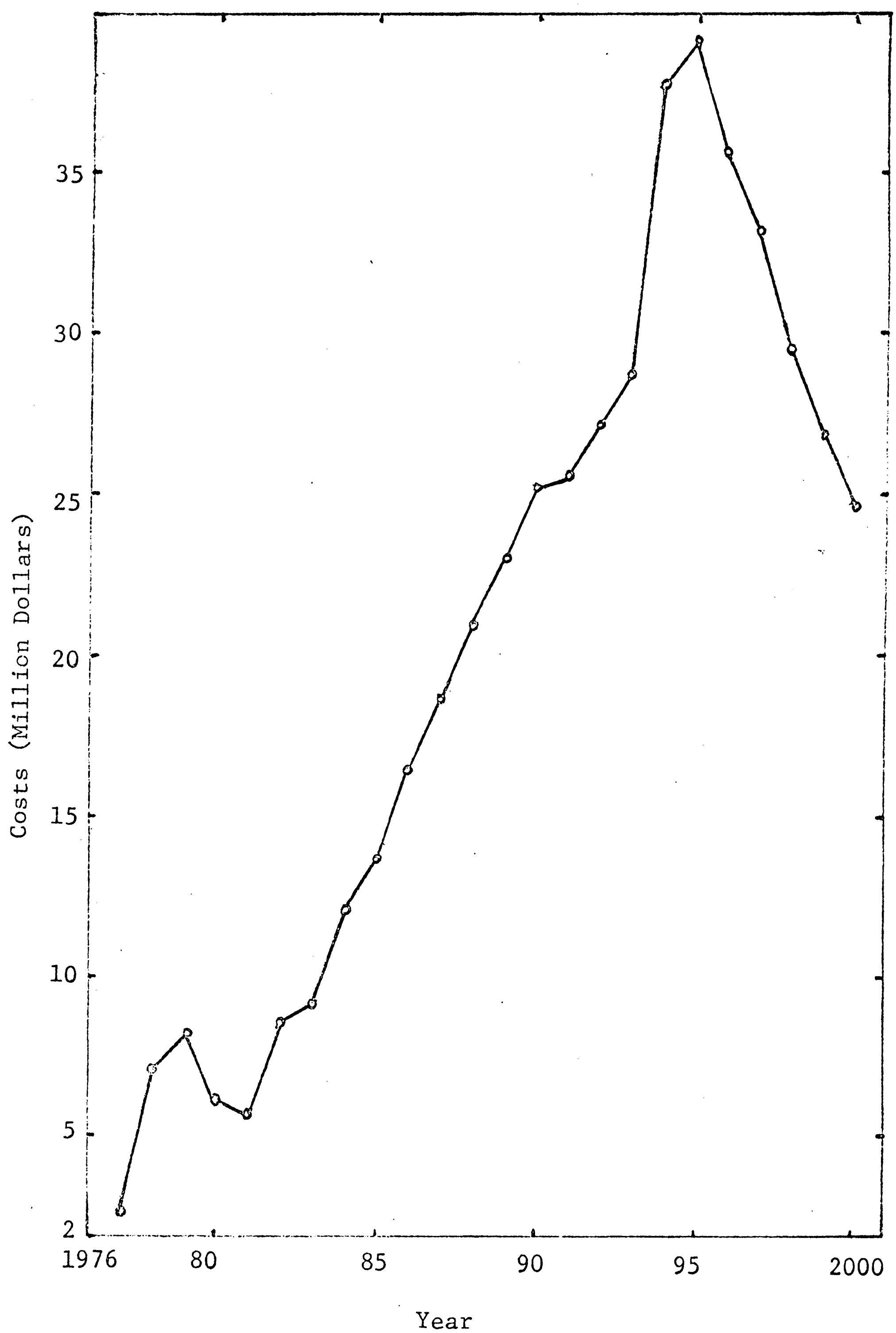


Figure 7.9. On-Site Storage Capacity Installation Costs - Zero Demand, M = 4.

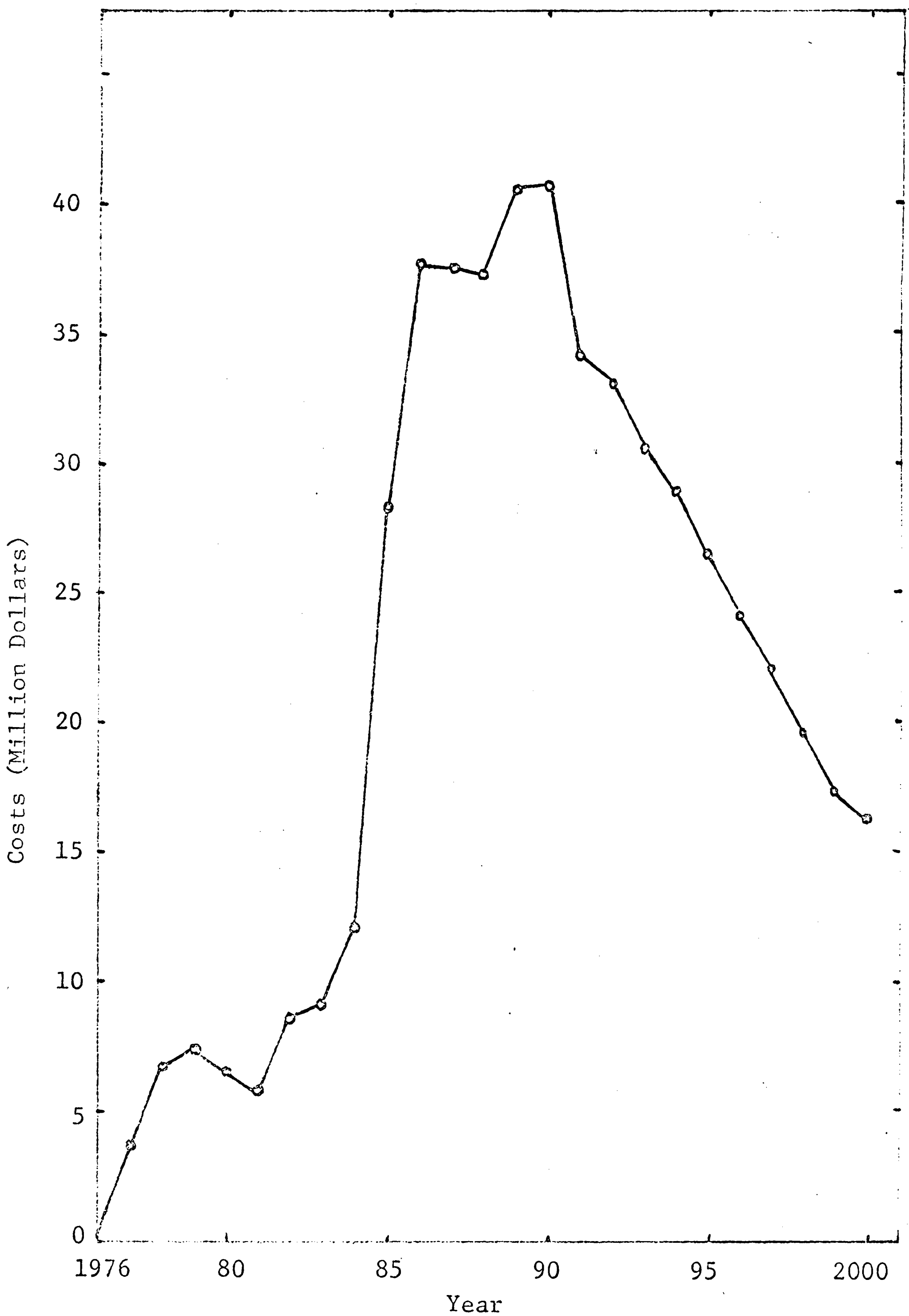


Figure 7.10. On-Site Storage Capacity Installation Costs - Zero Demand, M = 3.

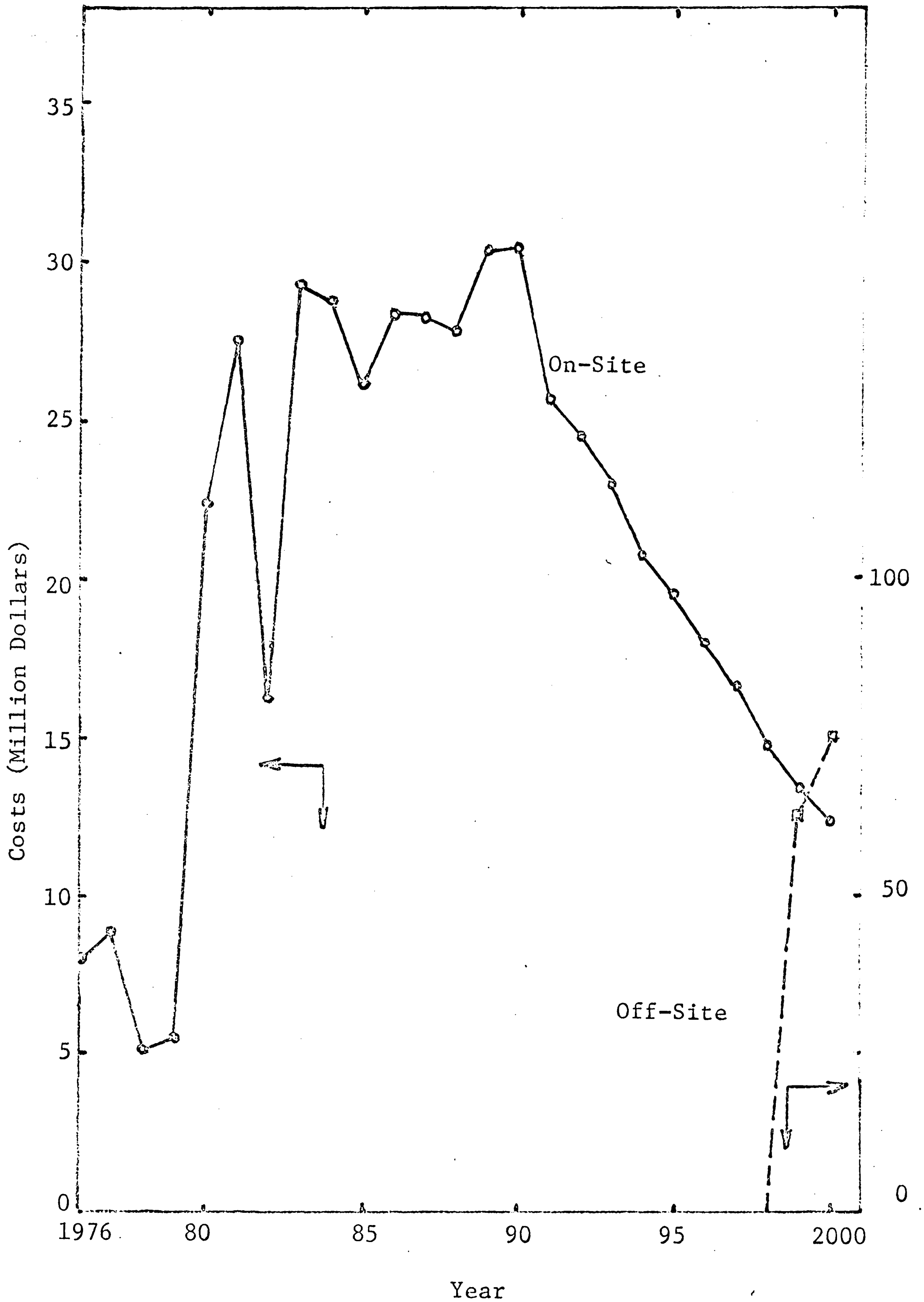


Figure 7.11. On-Site and Off-Site Storage Capacity Installation Costs - Zero Demand, M = 2.5.

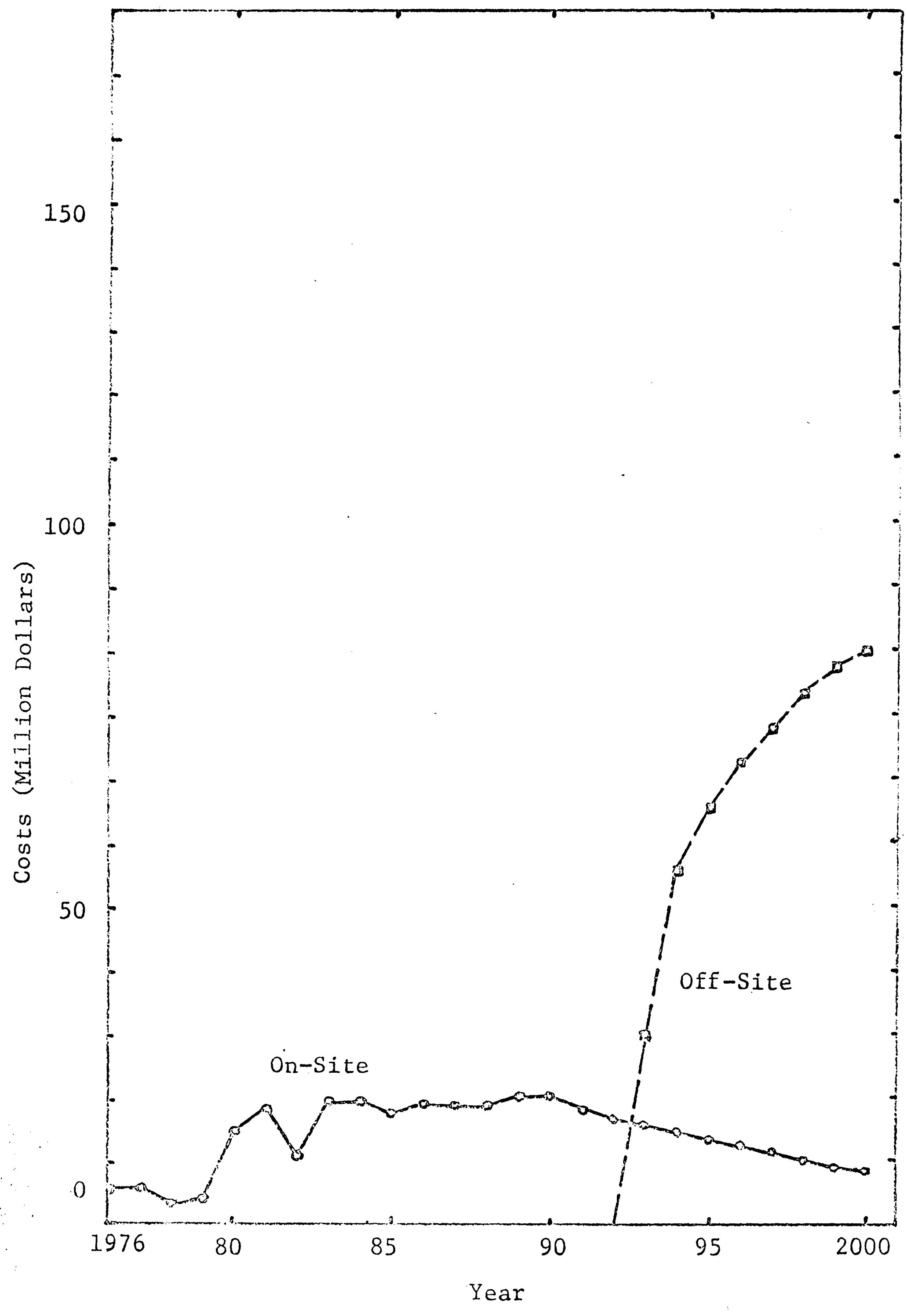


Figure 7.12. On-Site and Off-Site Storage Capacity Installation Costs - Zero Demand, M = 2.

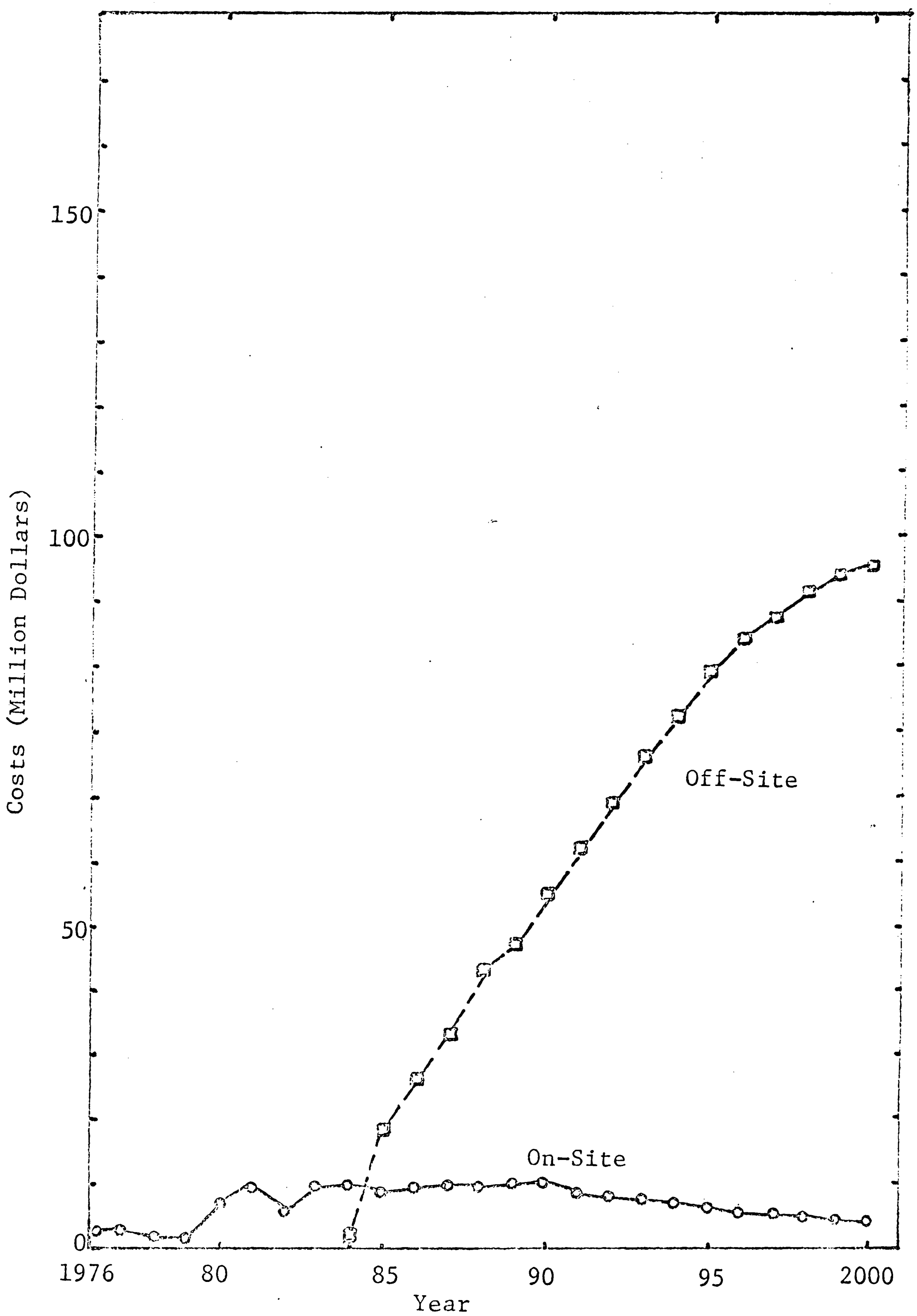


Figure 7.13. On-Site and Off-Site Storage Capacity Installation Costs - Zero Demand, M = 1.5.

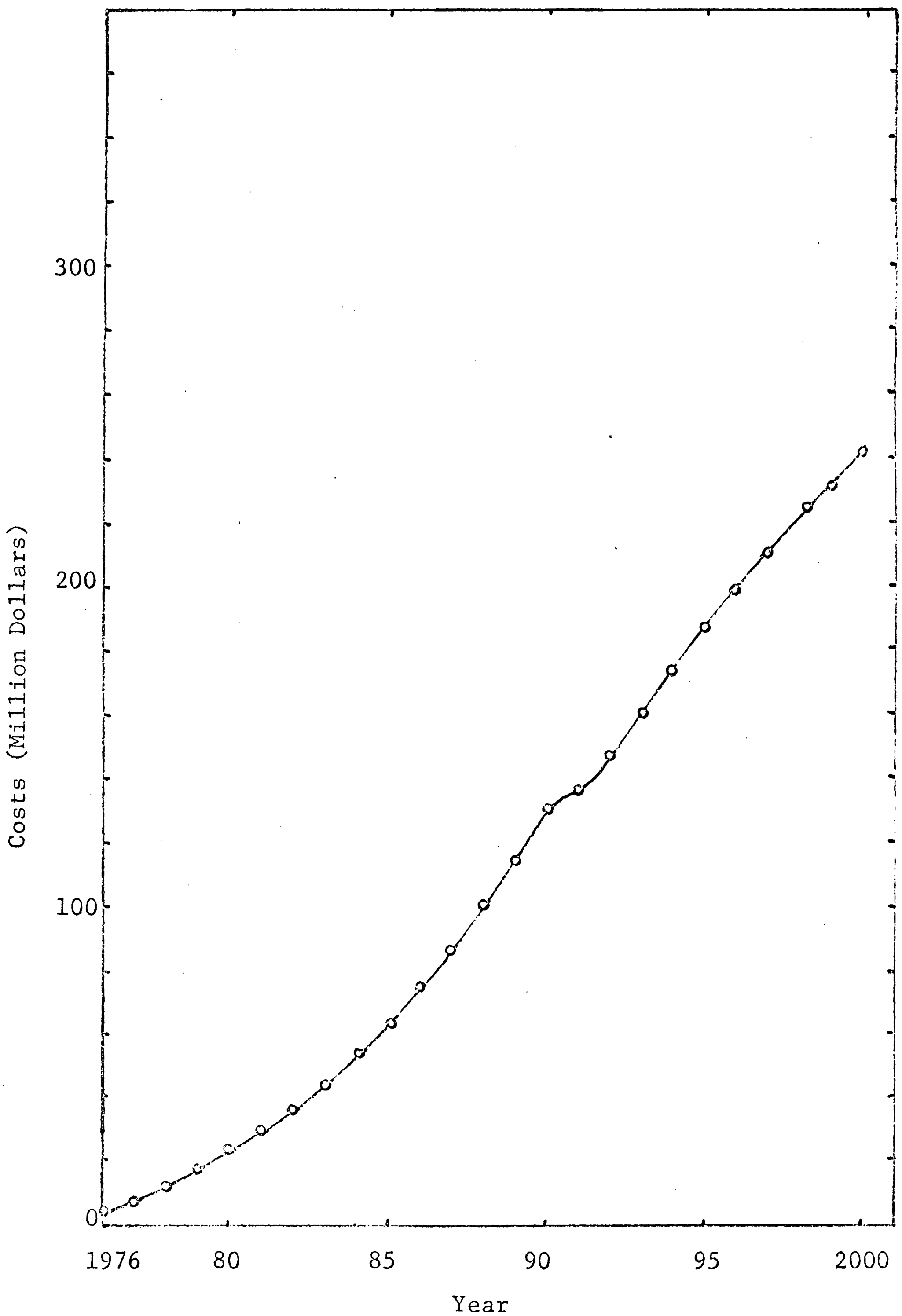


Figure 7.14. On-Site Spent Fuel Storage Costs
- Zero Demand, Unconstrained Case.

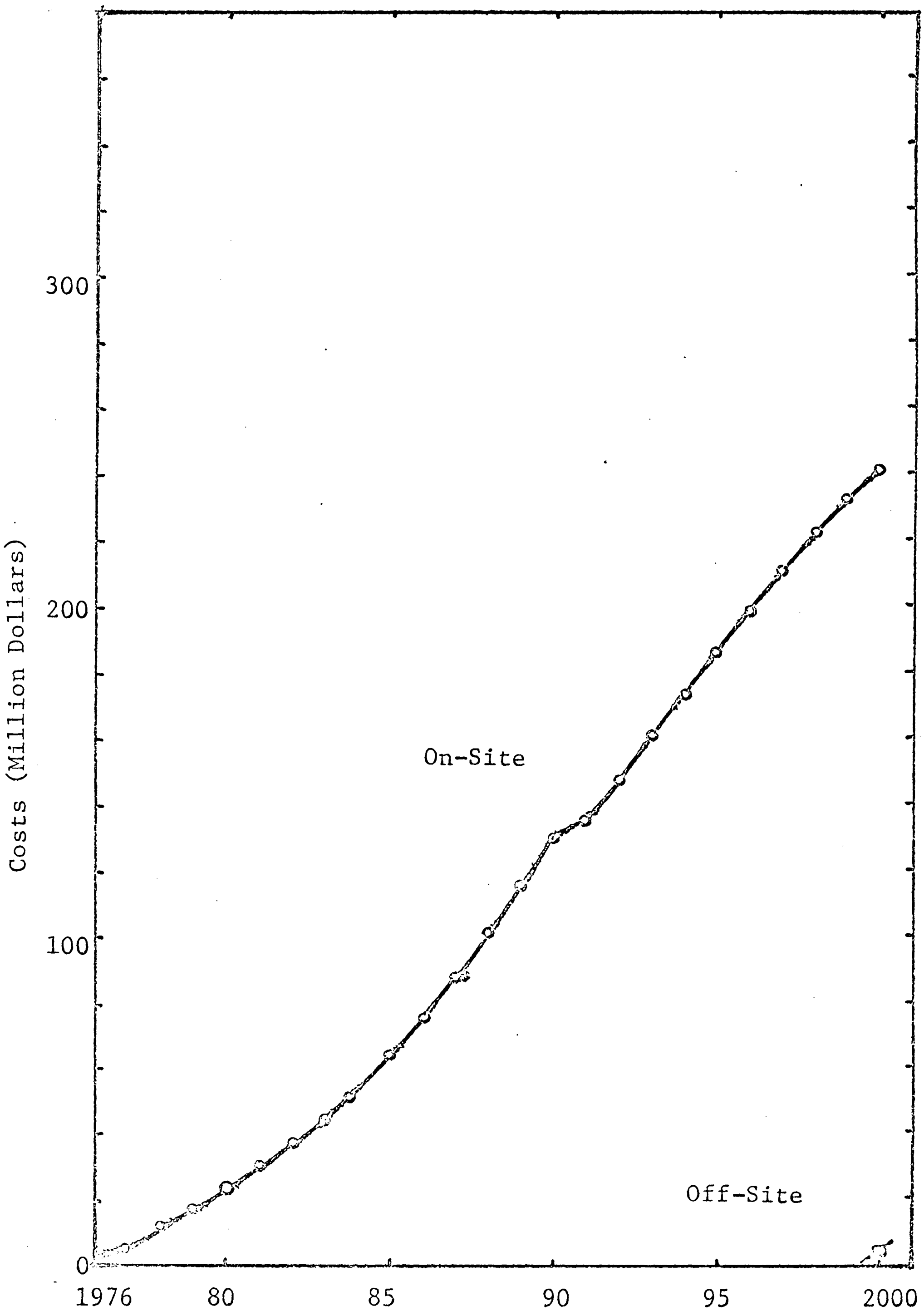


Figure 7.15. On-Site and Off-Site Spent Fuel Storage Costs - Zero Demand, M = 3, 4.

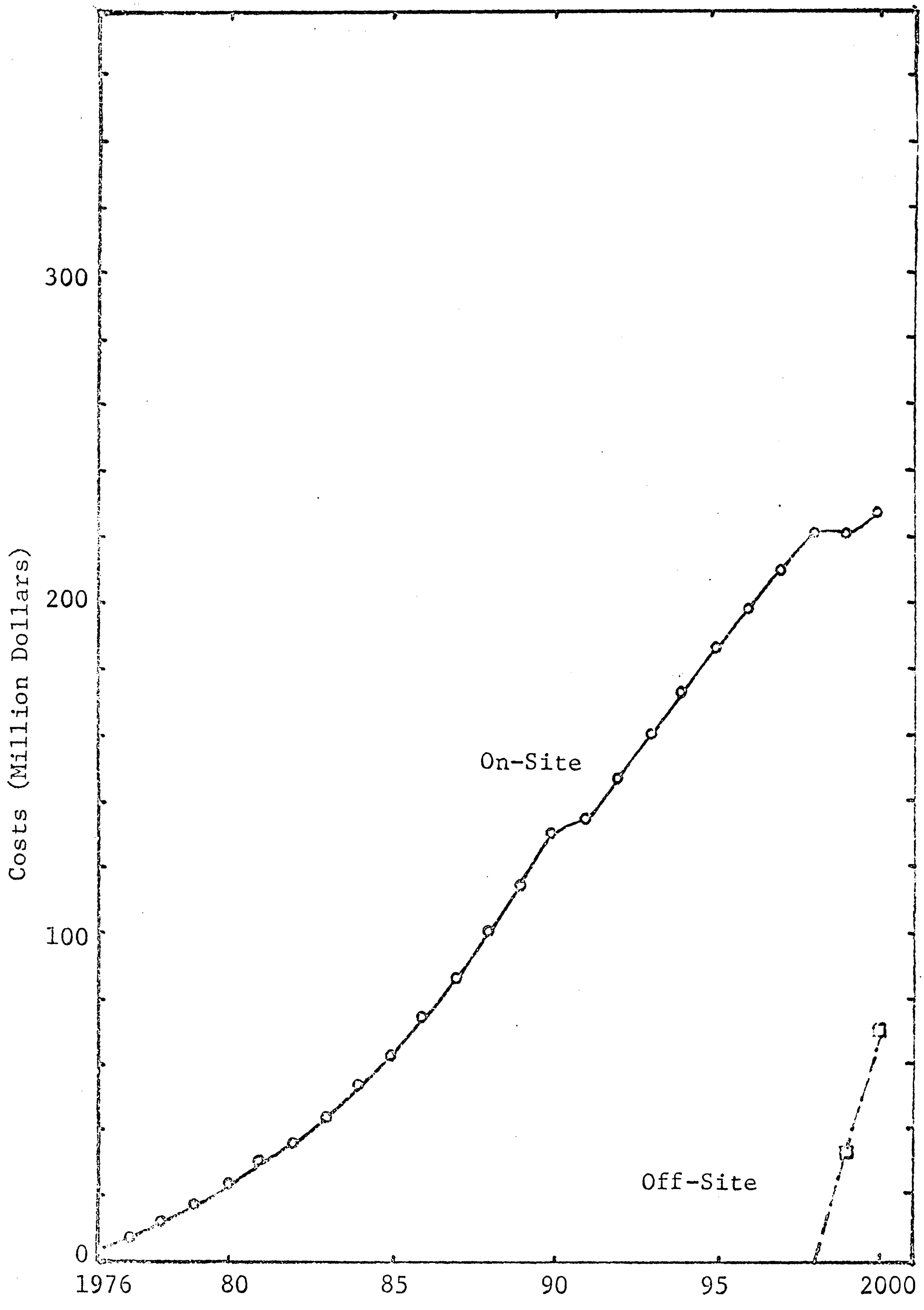


Figure 7.16. On-Site and Off-Site Spent Fuel Storage Costs - Zero Demand, M = 2.5.

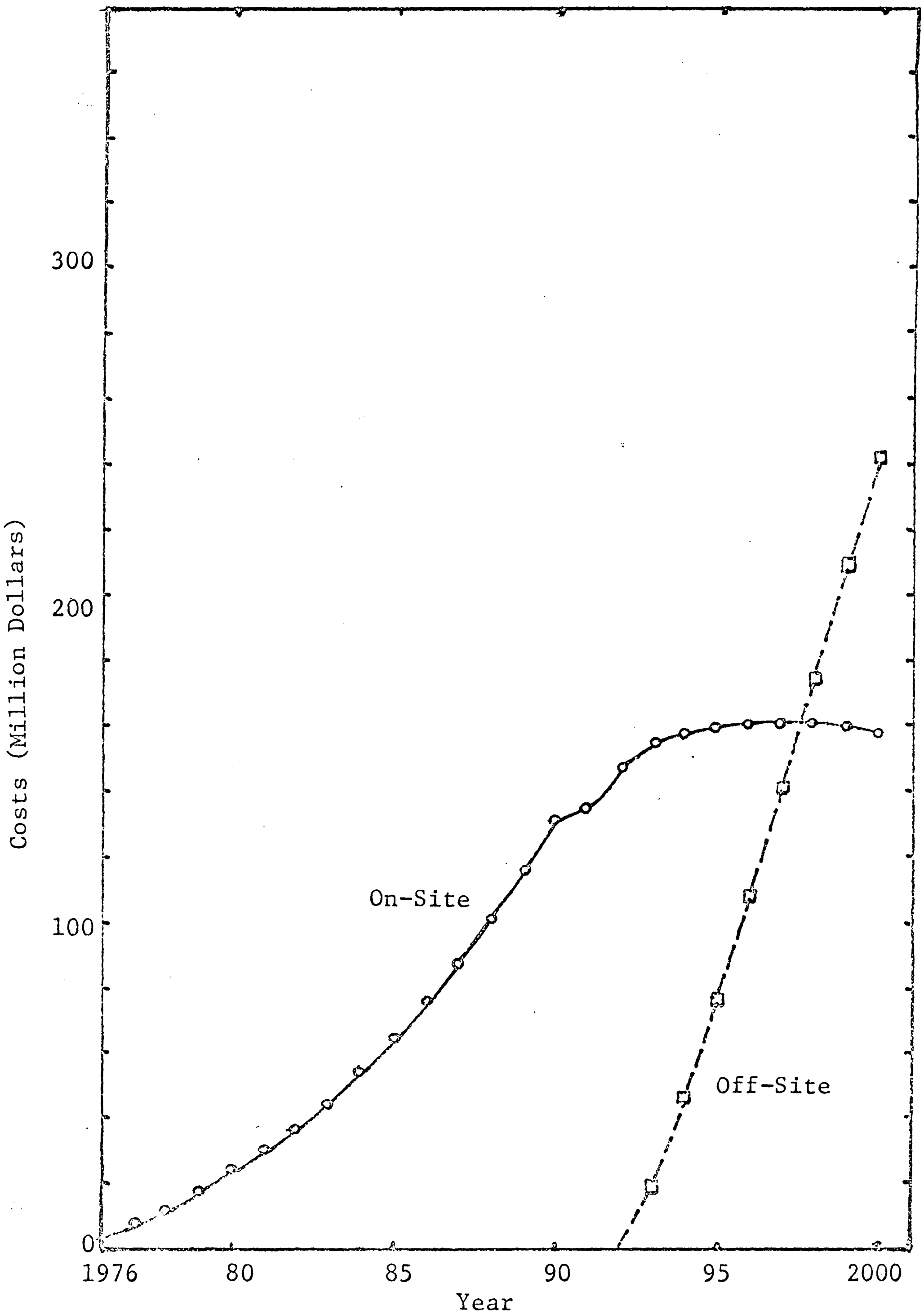


Figure 7.17. On-Site and Off-Site Spent Fuel Storage Costs - Zero Demand, M = 2.

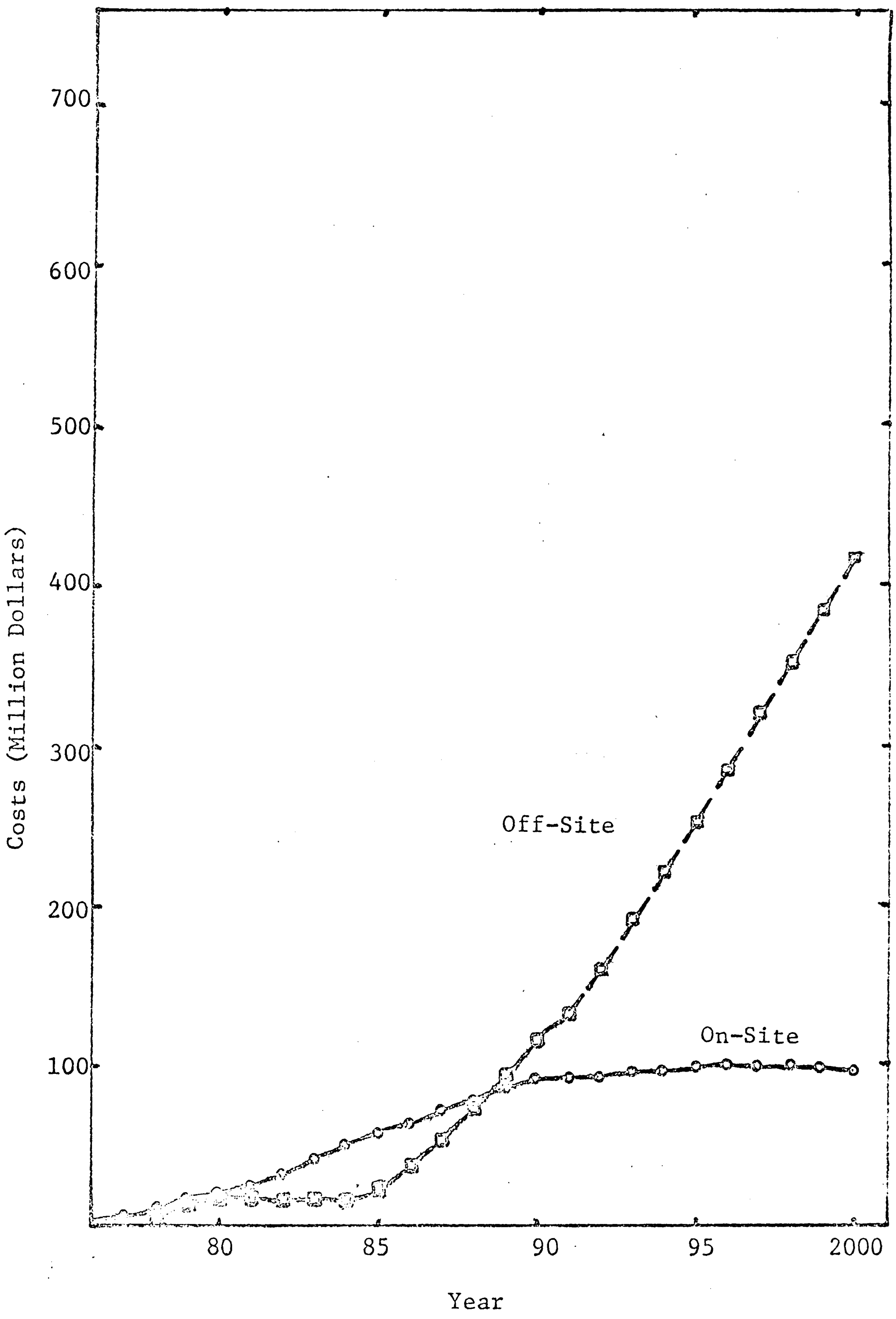


Figure 7.18. On-Site and Off-Site Spent Fuel Storage Costs - Zero Demand, M = 1.5.

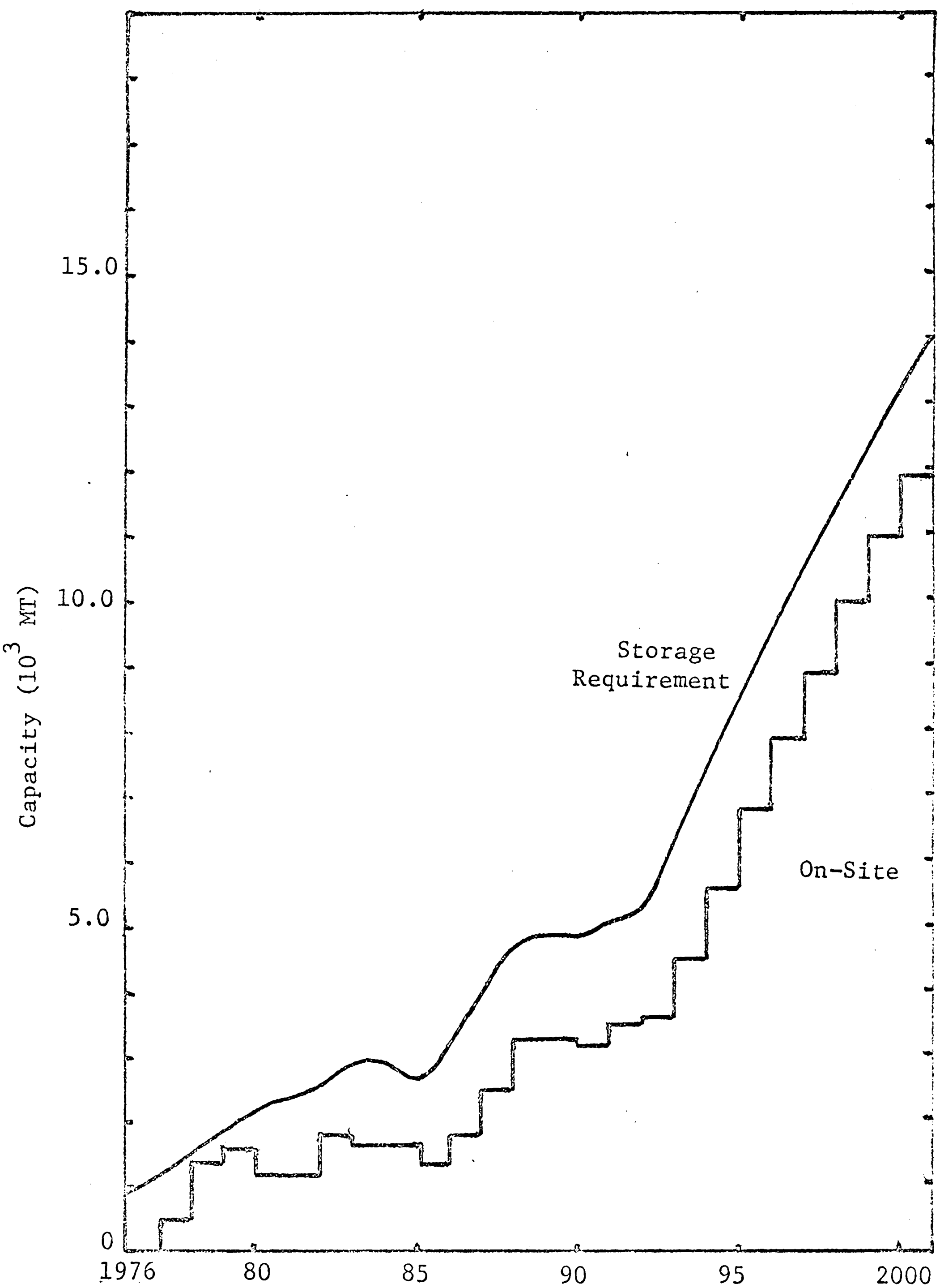


Figure 7.19. On-Site and Off-Site Storage Capacity Growth - Pessimistic Reprocessing Scenario, Unconstrained Case.

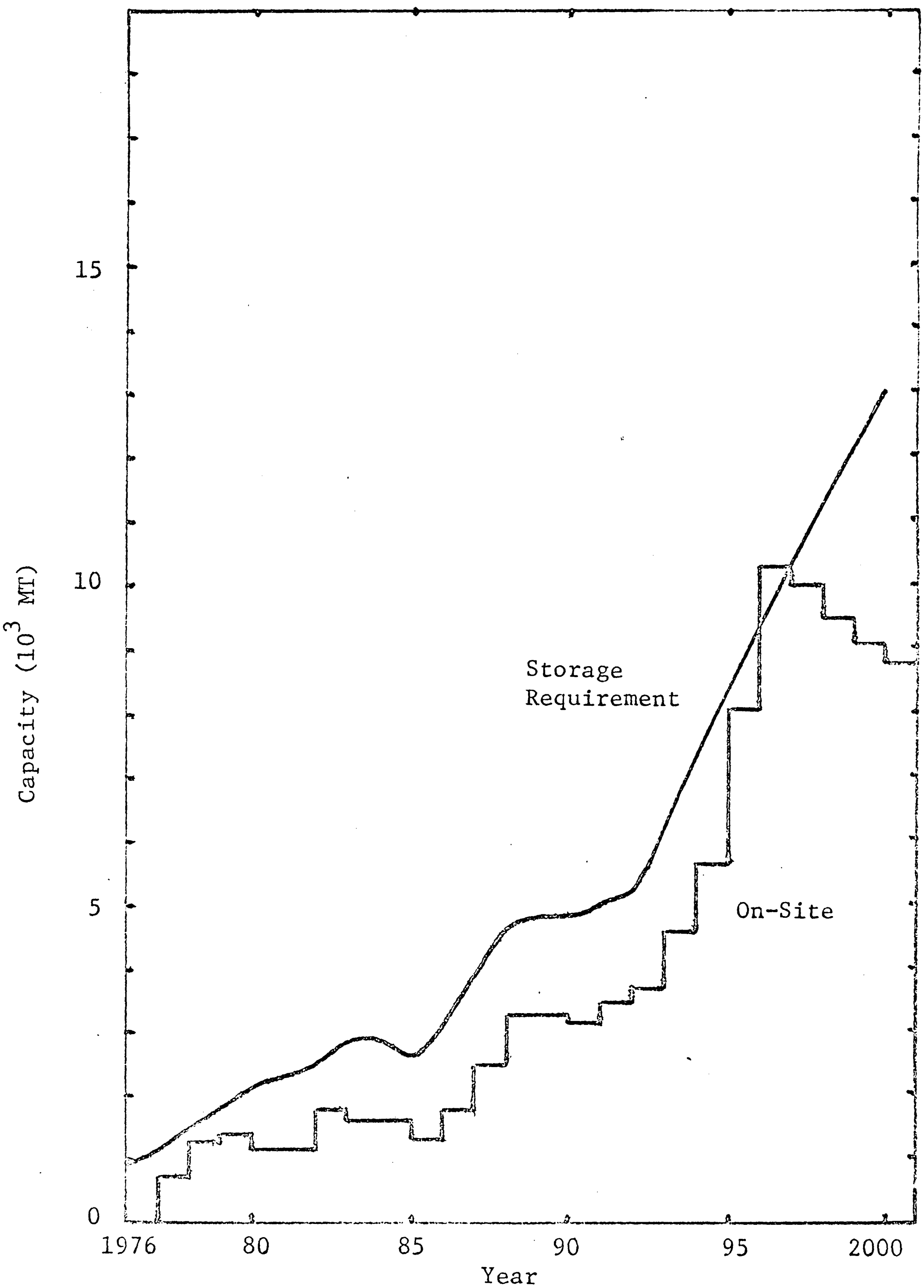


Figure 7.20. On-Site and Off-Site Storage Capacity Growth - Pessimistic Reprocessing Scenario, M = 3.

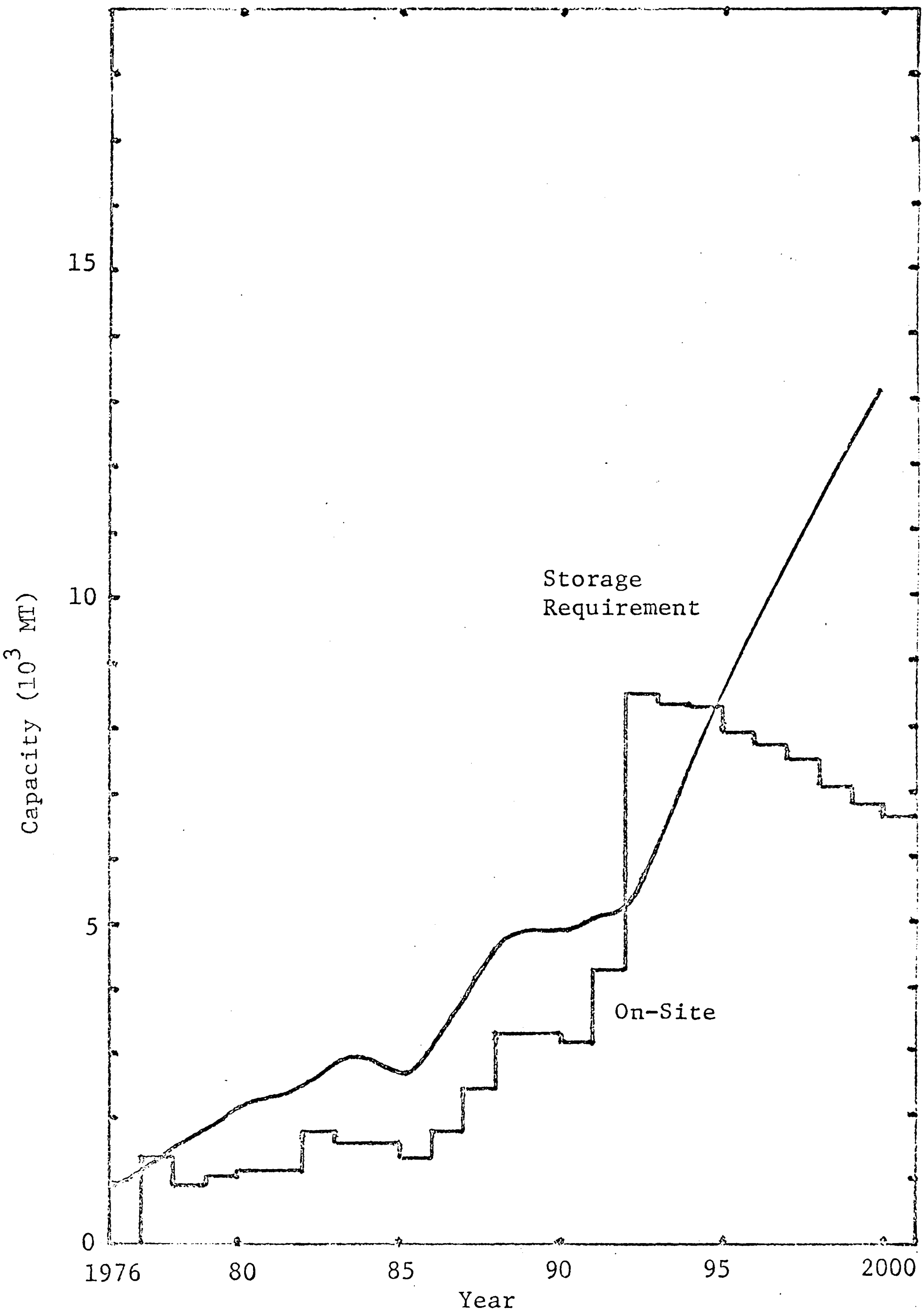


Figure 7.21. On-Site and Off-Site Storage Capacity Growth - Pessimistic Reprocessing Scenario, M = 2.5.

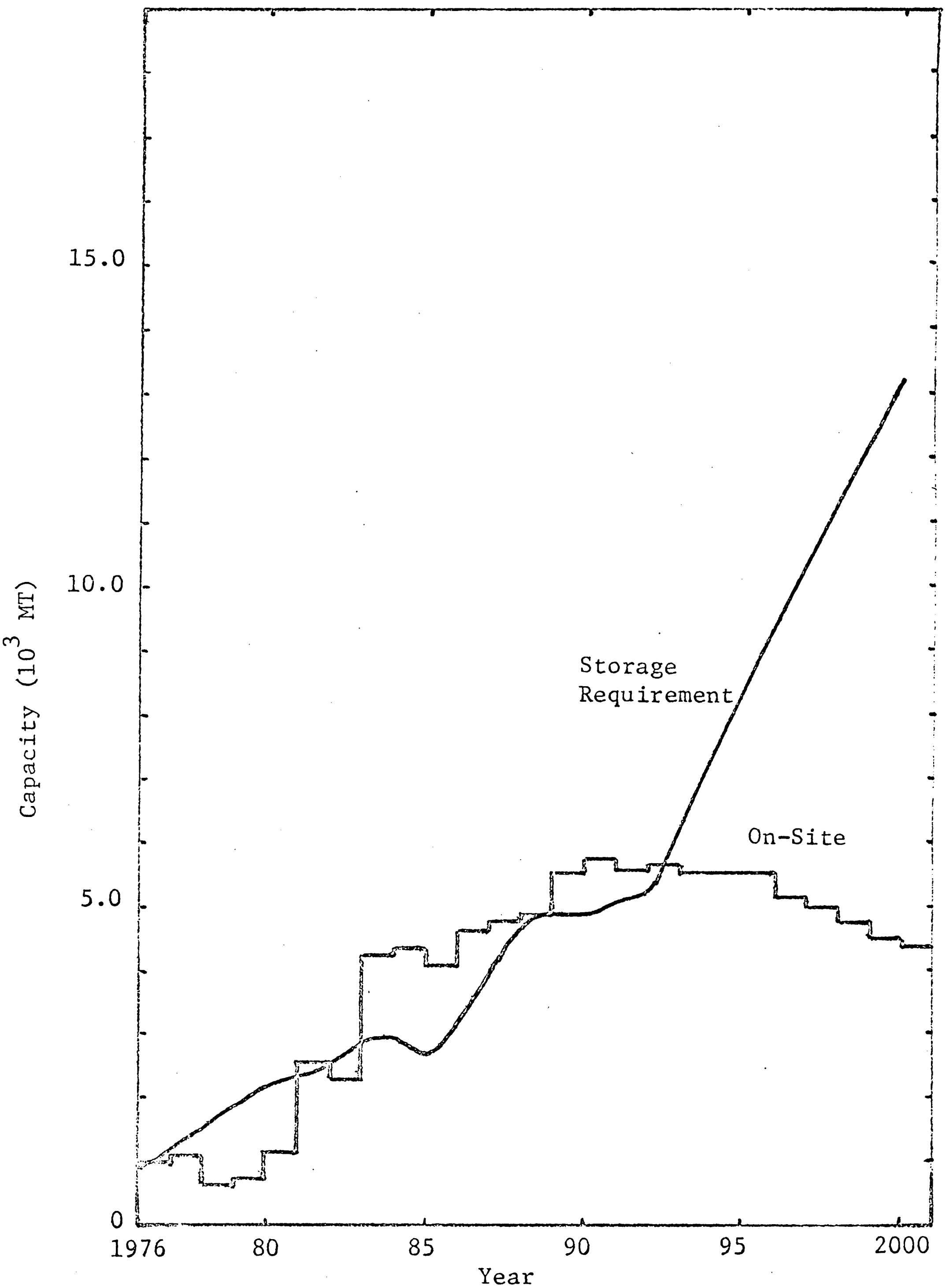


Figure 7.22. On-Site and Off-Site Storage Capacity Growth - Pessimistic Reprocessing Scenario, M = 2.

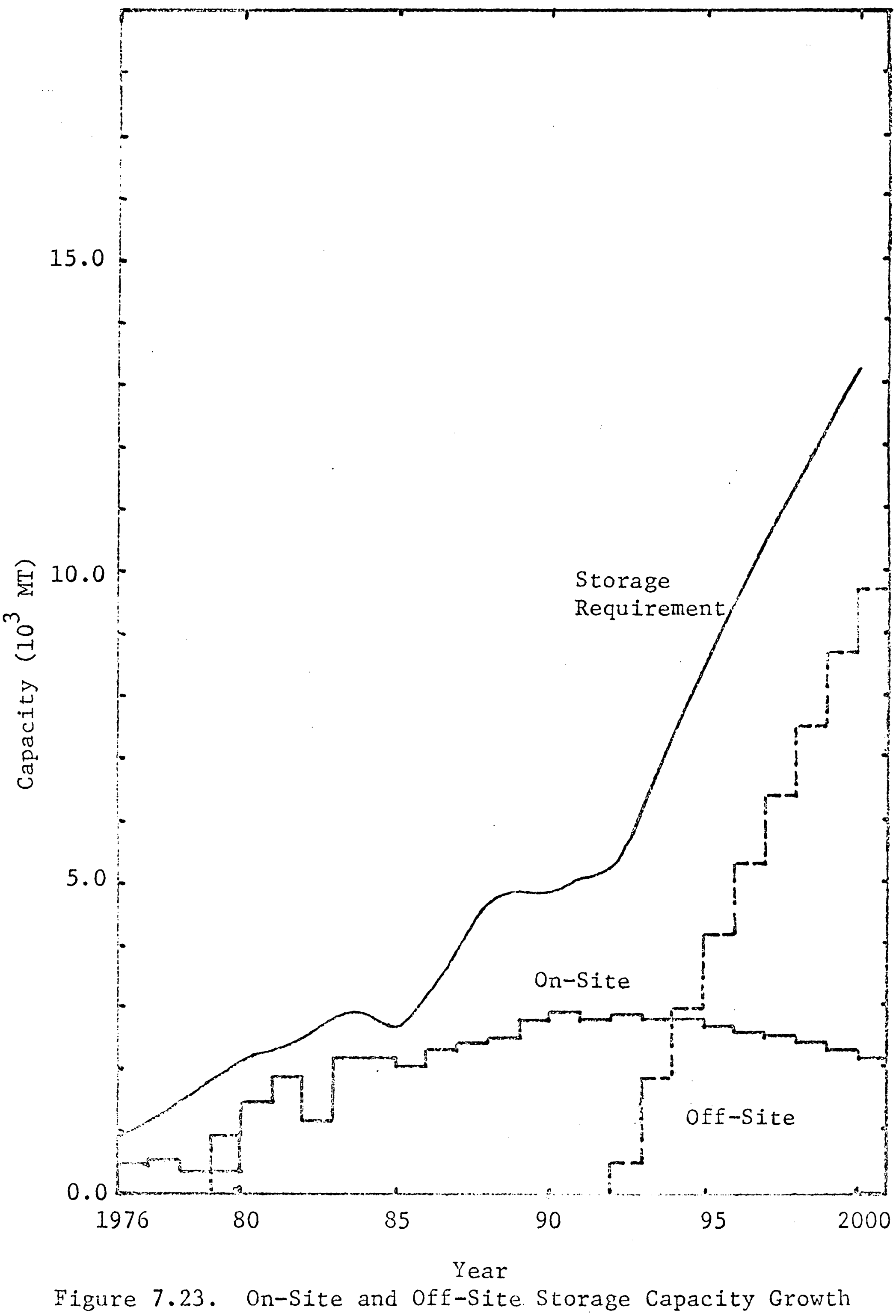


Figure 7.23. On-Site and Off-Site Storage Capacity Growth - Pessimistic Reprocessing Scenario, M = 1.5.

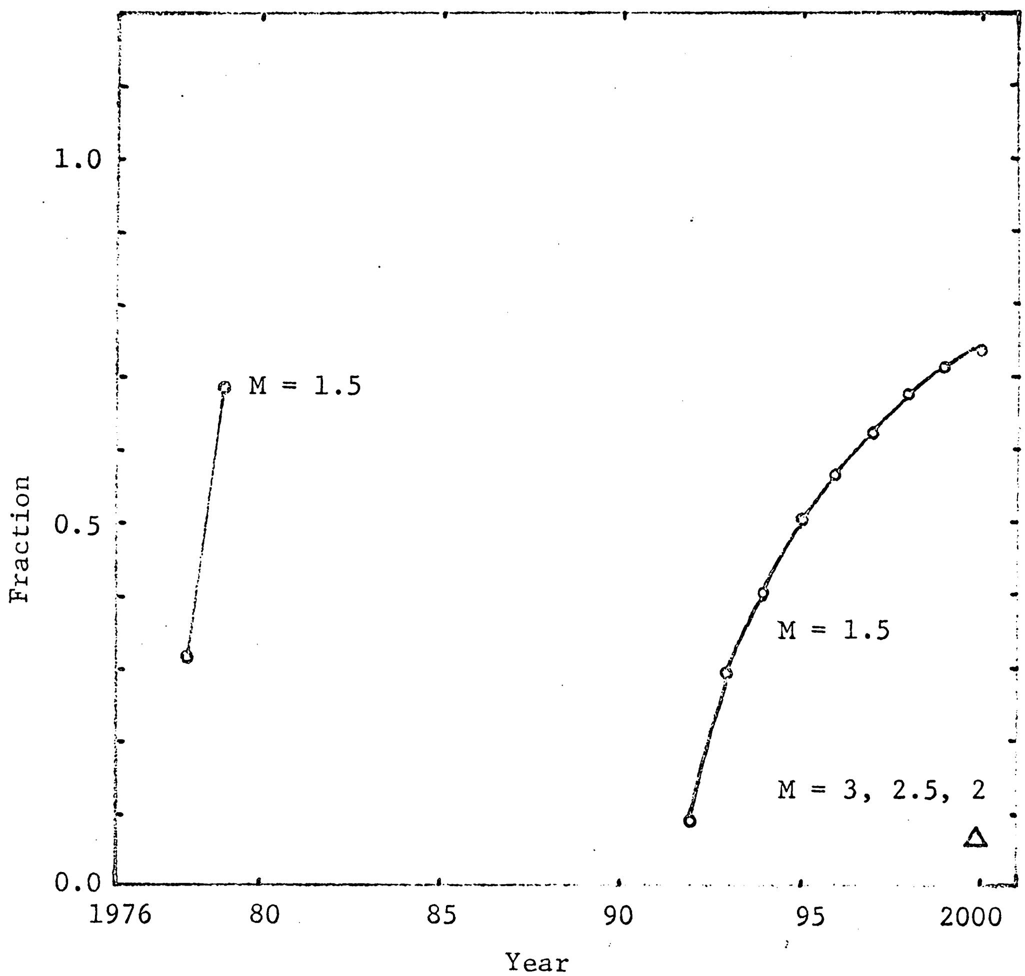


Figure 7.24. Fraction of Spent Fuel Transferred Off-Site - Pessimistic Reprocessing Scenario.

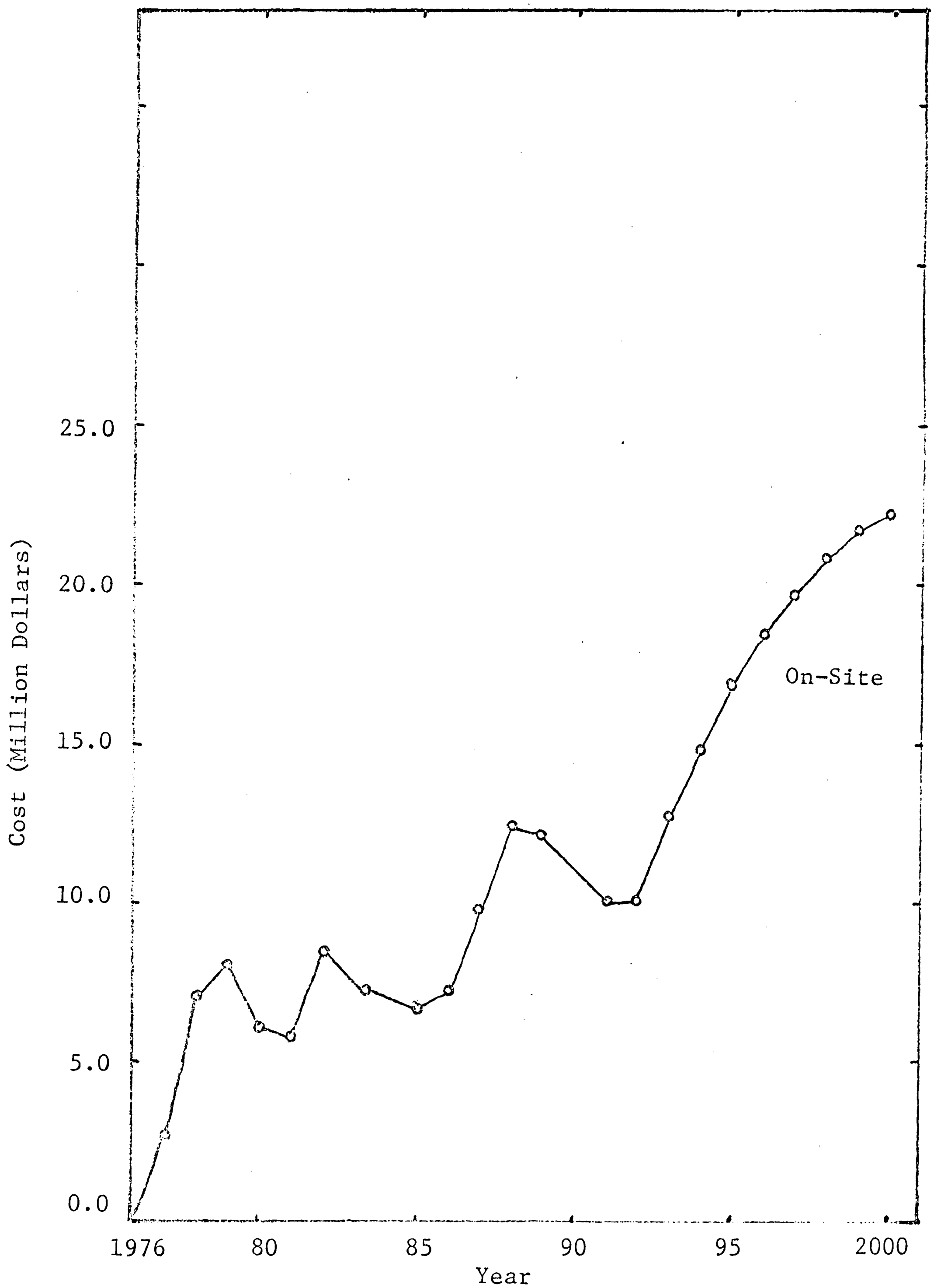


Figure 7.25. On-Site and Off-Site Storage Capacity Installation Costs - Pessimistic Reprocessing Scenario, Unconstrained Case.

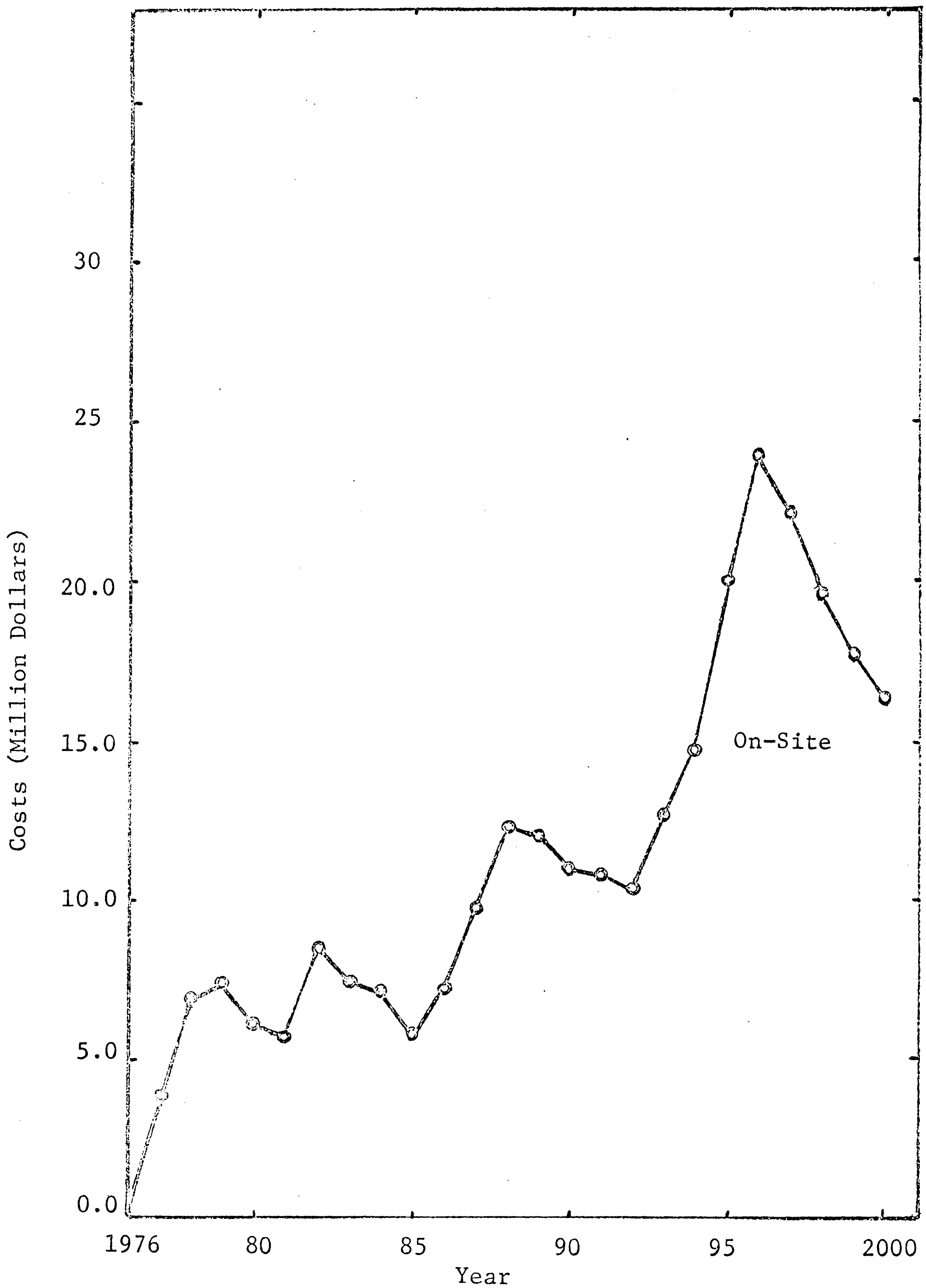


Figure 7.26. On-Site and Off-Site Storage Capacity Installation Costs, Pessimistic Reprocessing Scenario, M = 3.

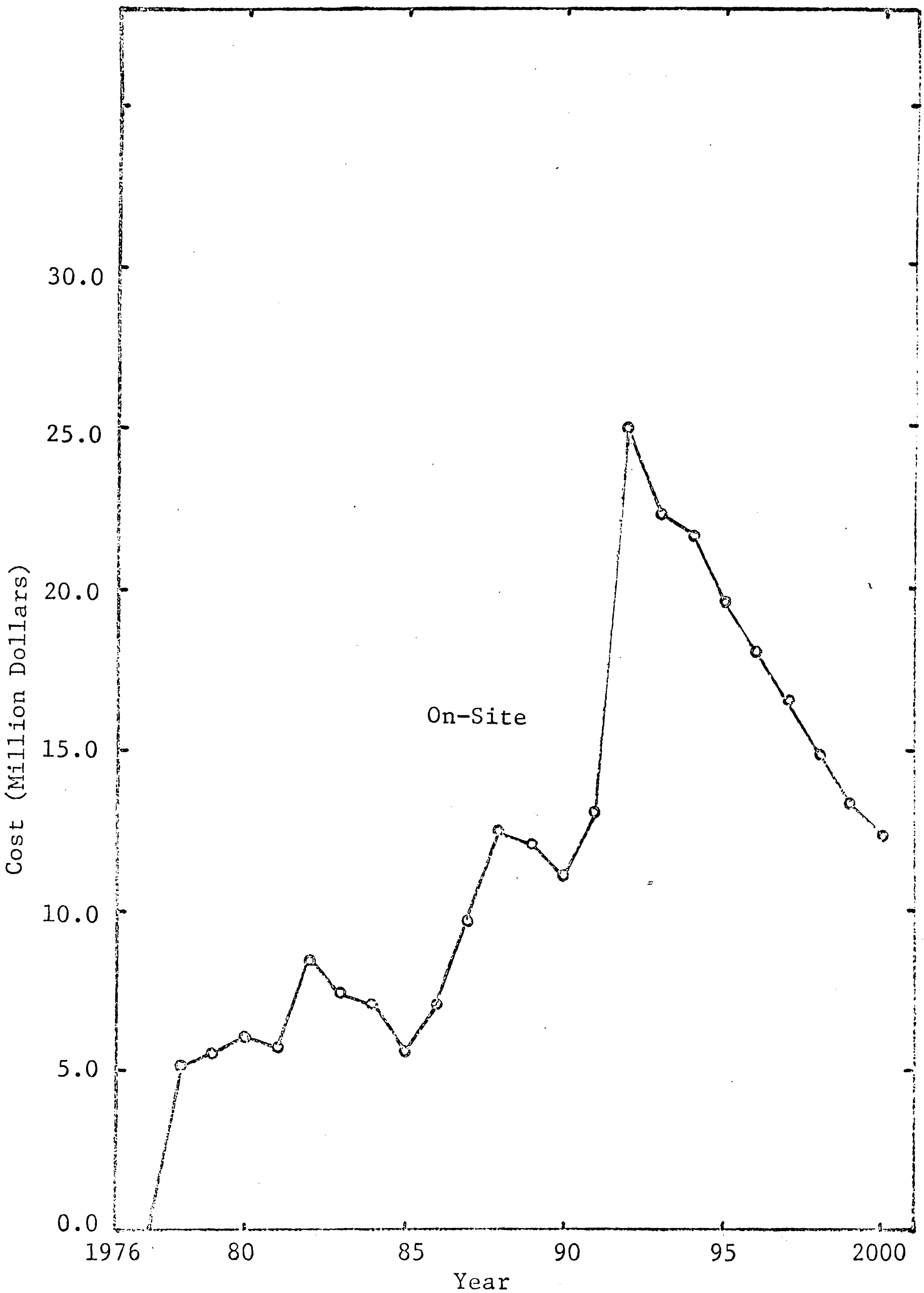


Figure 7.27. On-Site and Off-Site Storage Capacity Installation Costs, Pessimistic Reprocessing Scenario, M = 2.5.

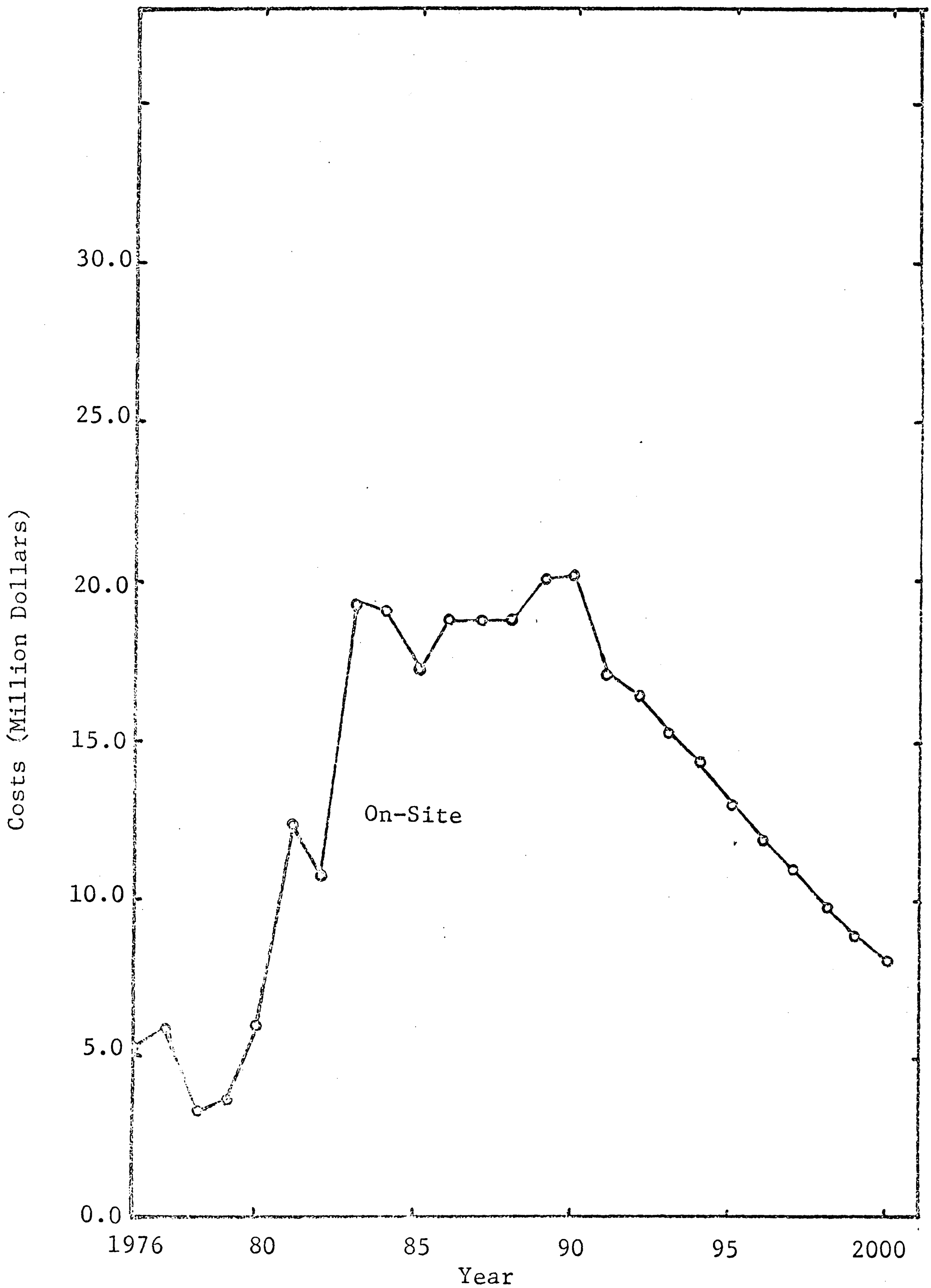


Figure 7.28. On-Site and Off-Site Storage Capacity Installation Costs, Pessimistic Reprocessing Scenario, M = 2.

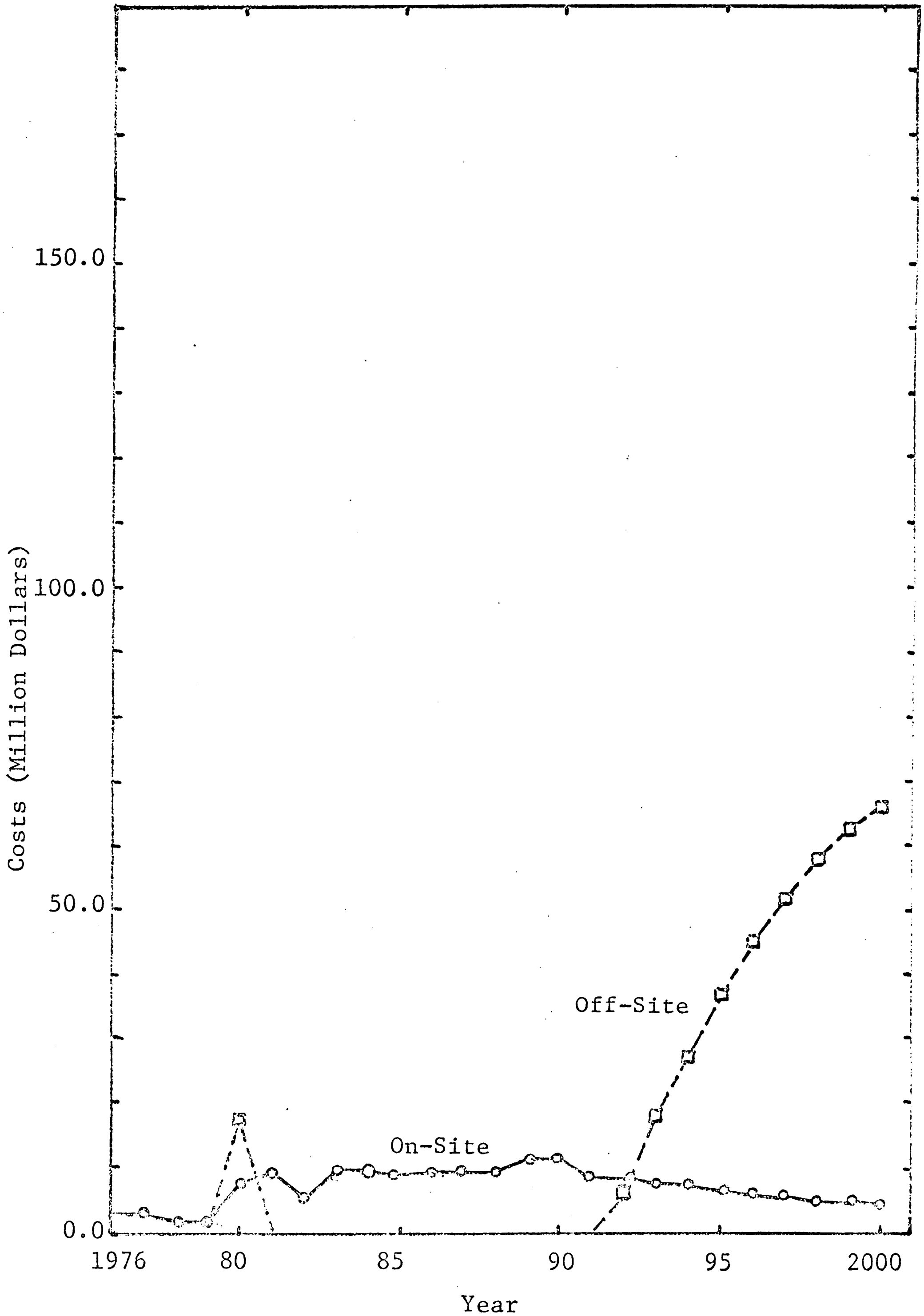


Figure 7.29. On-Site and Off-Site Storage Capacity Installation Costs - Pessimistic Reprocessing Scenario, M = 1.5.

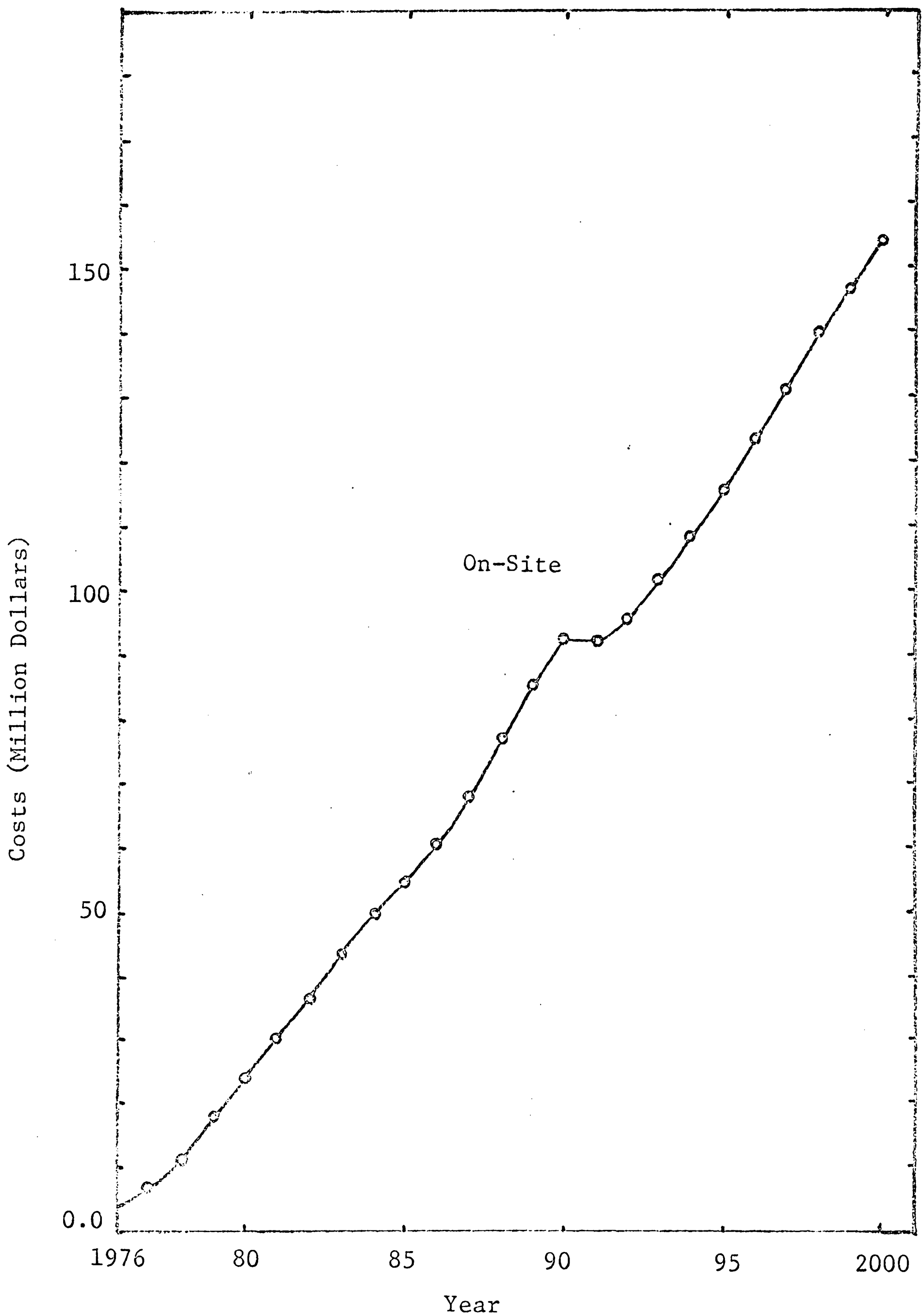


Figure 7.30. On-Site and Off-Site Spent Fuel Storage Costs - Pessimistic Reprocessing Scenario, Unconstrained Case.

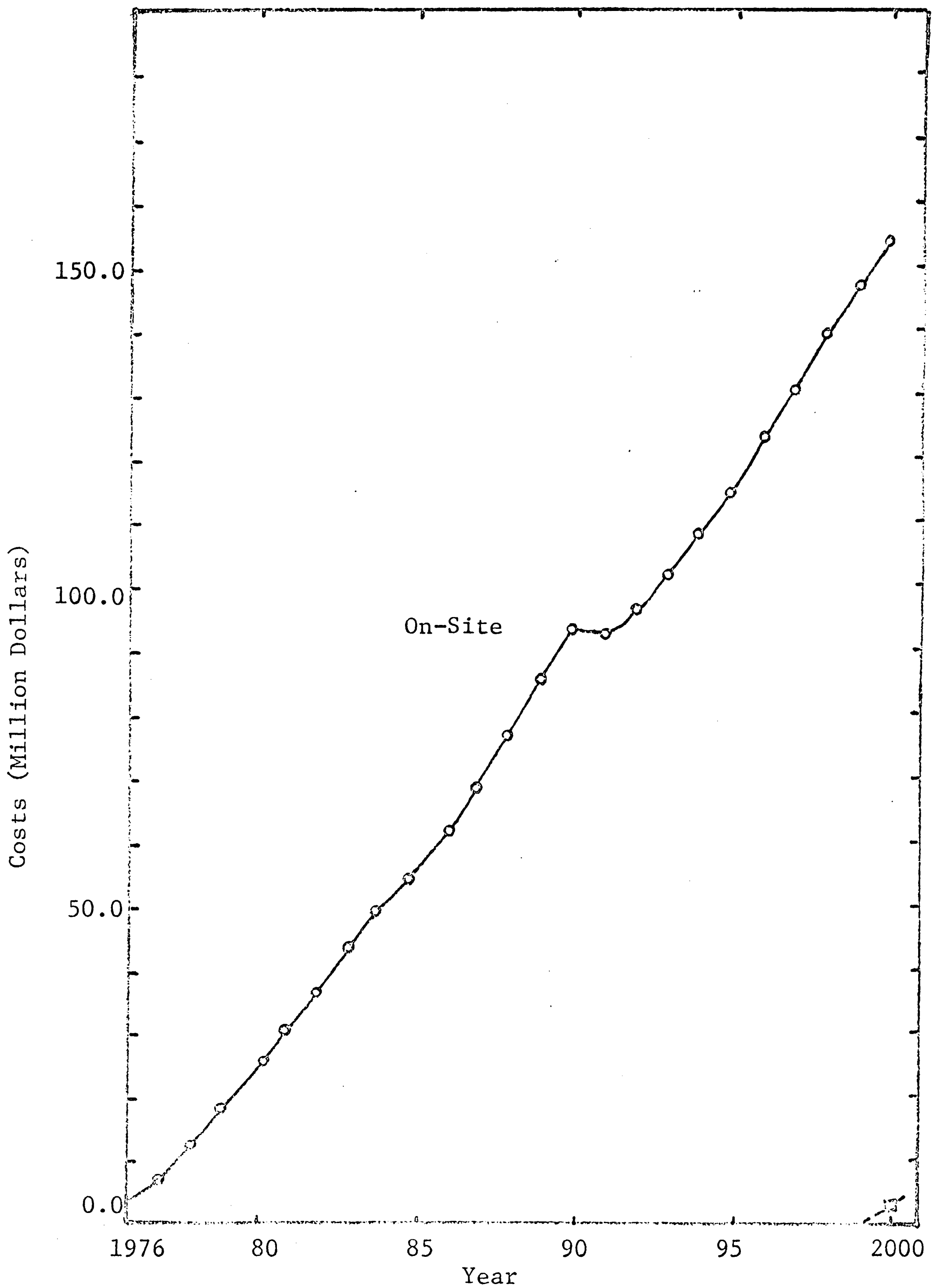


Figure 7.31. On-Site and Off-Site Spent Fuel Storage Costs - Pessimistic Reprocessing Scenario, M = 3, 2.5, 2.

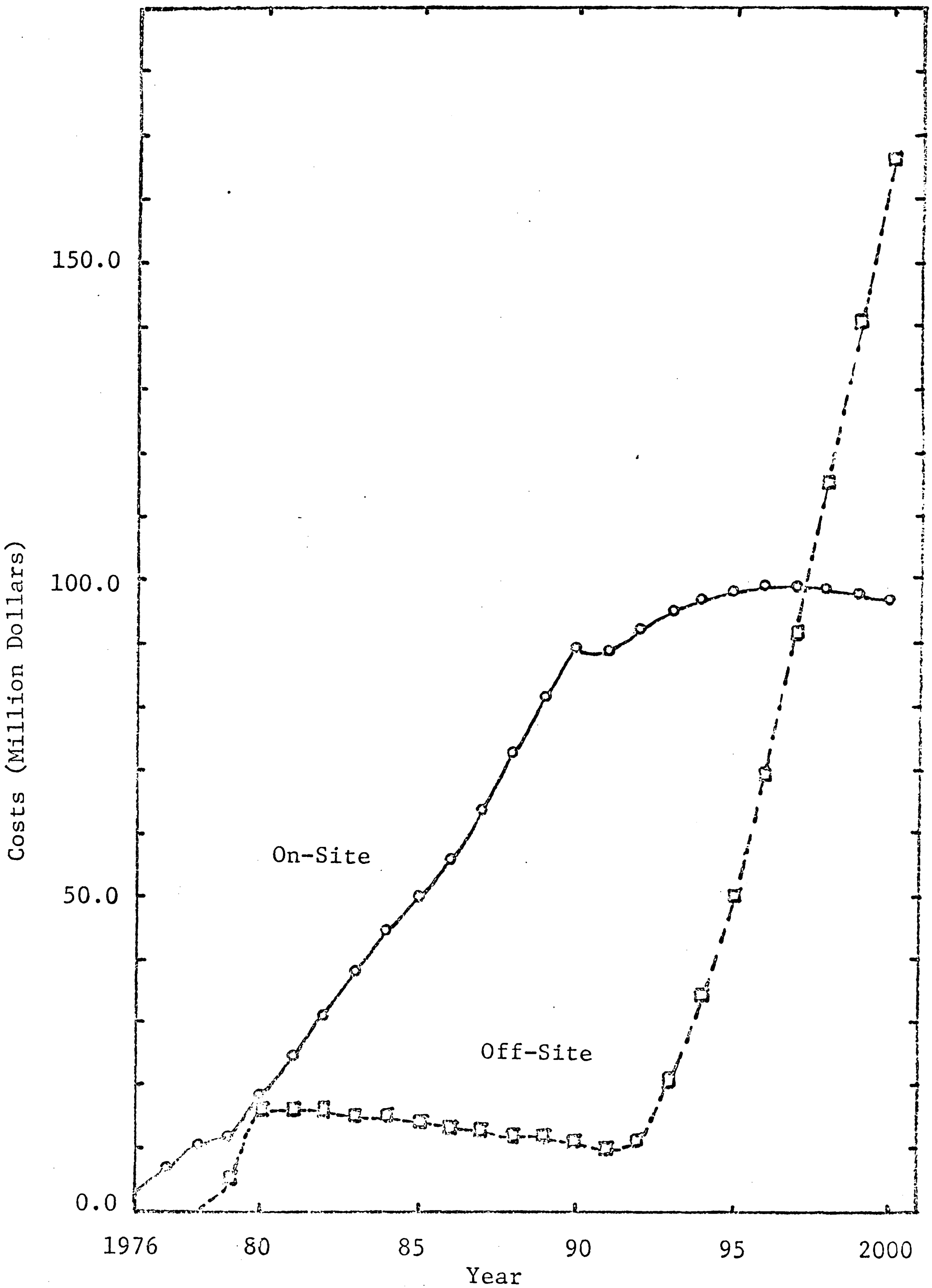


Figure 7.32. On-Site and Off-Site Spent Fuel Storage Costs - Pessimistic Reprocessing Scenario, M = 1.5.

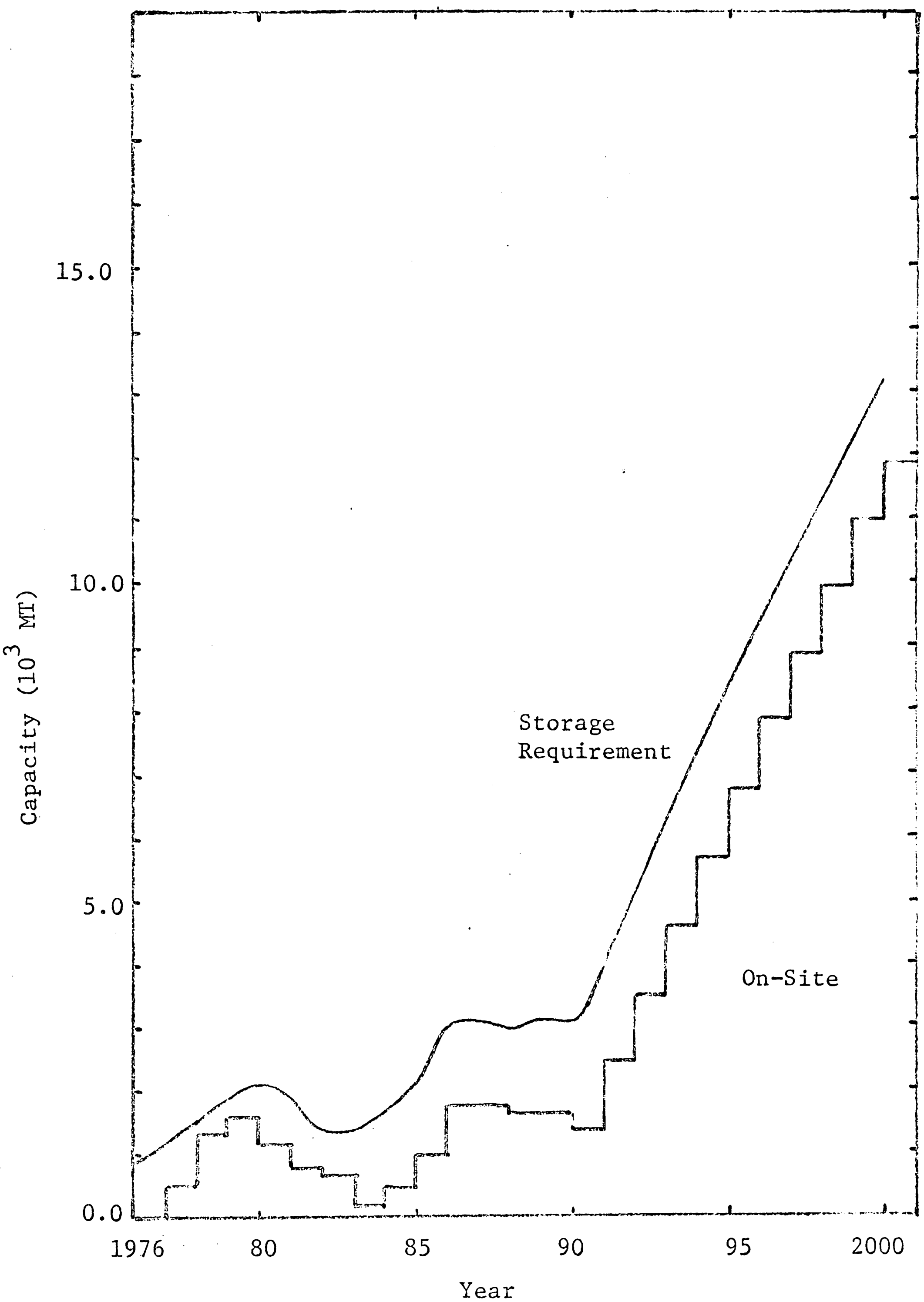


Figure 7.33. On-Site and Off-Site Storage Capacity Growth - Realistic Reprocessing Forecast, Unconstrained Case.

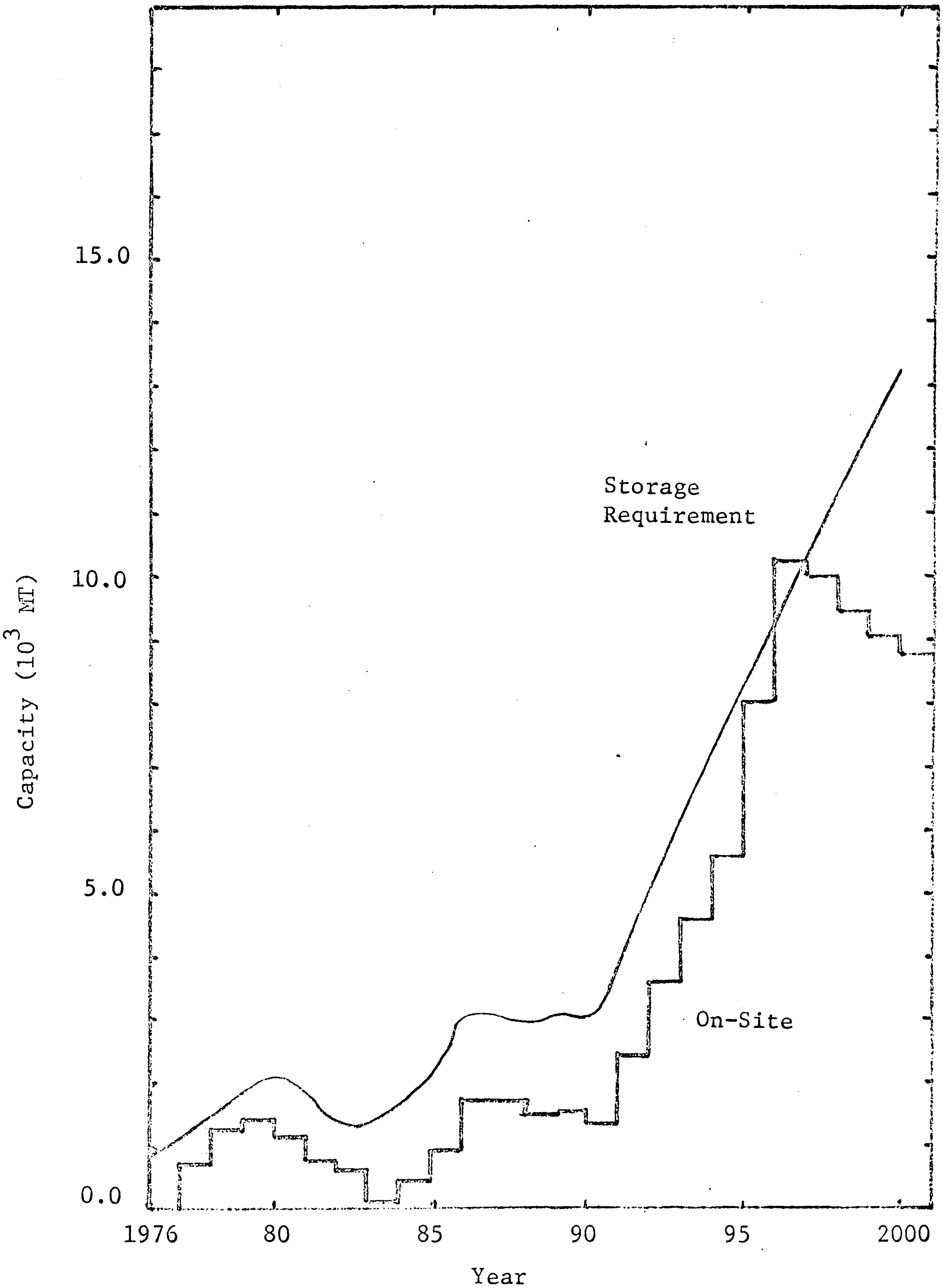


Figure 7.34. On-Site and Off-Site Storage Capacity Growth - Realistic Reprocessing Scenario, M = 3.

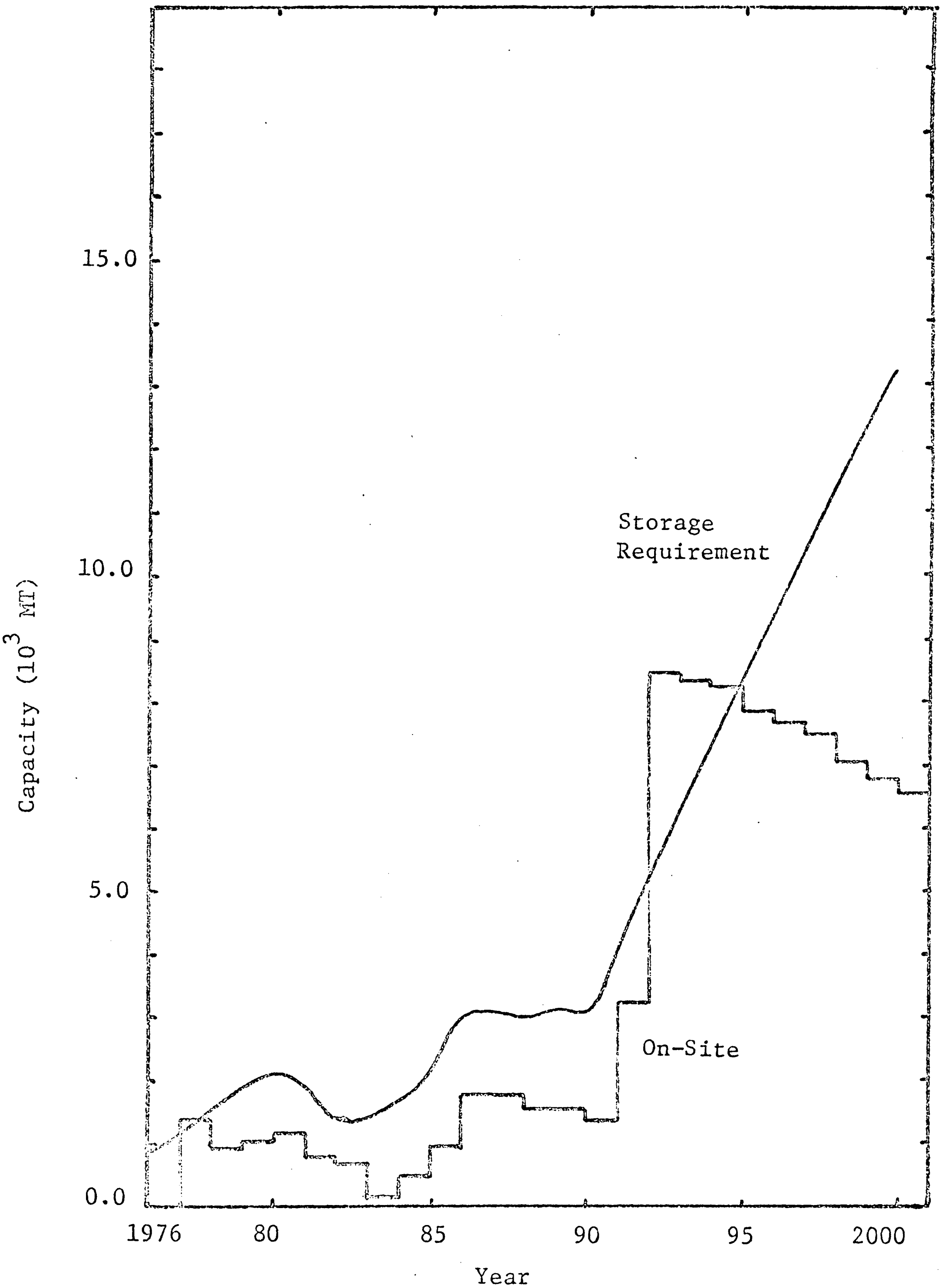


Figure 7.35. On-Site and Off-Site Storage Capacity Growth - Realistic Reprocessing Scenario, M = 2.5.

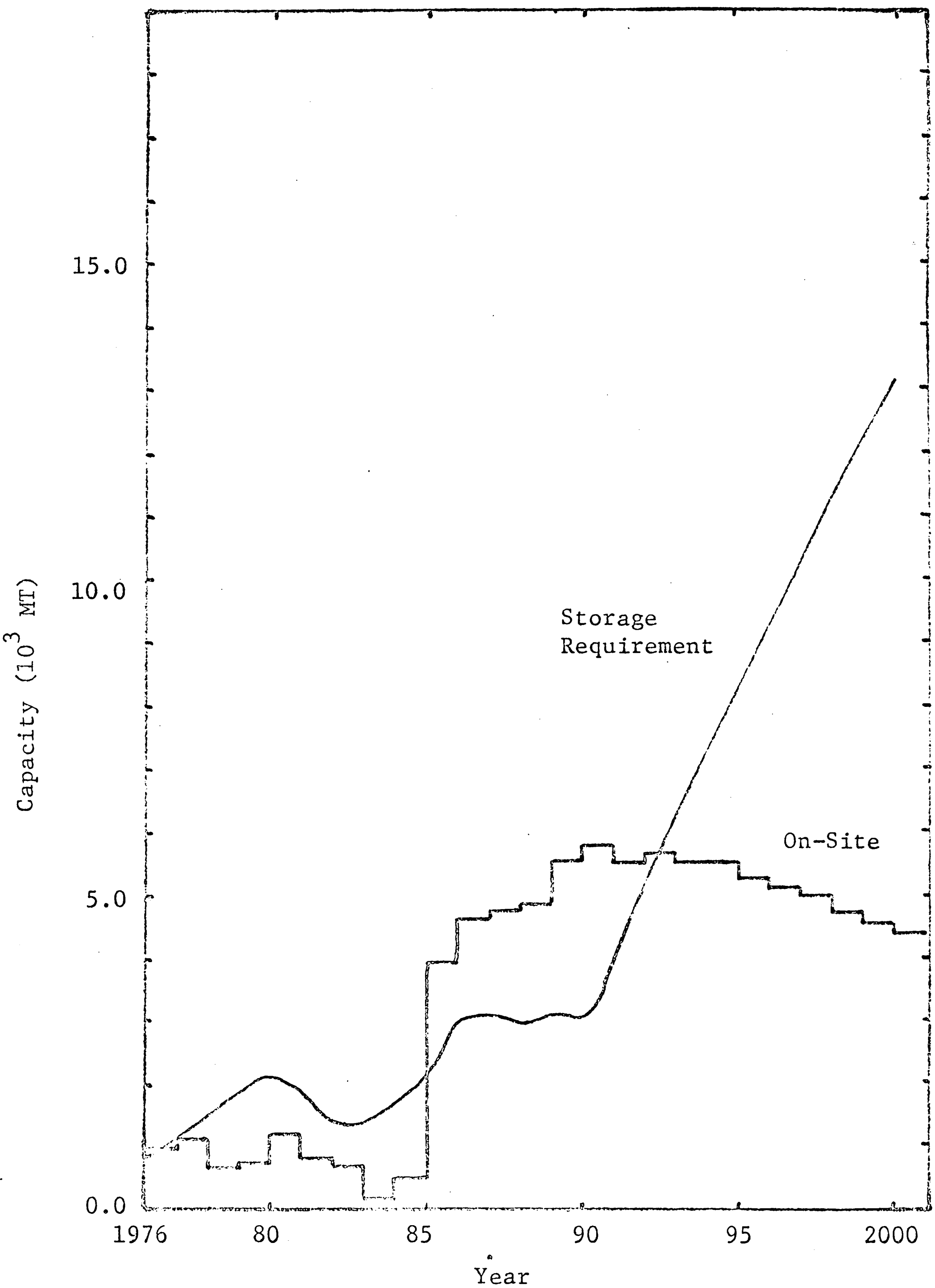


Figure 7.36. On-Site and Off-Site Storage Capacity Growth - Realistic Reprocessing Scenario, M = 2.

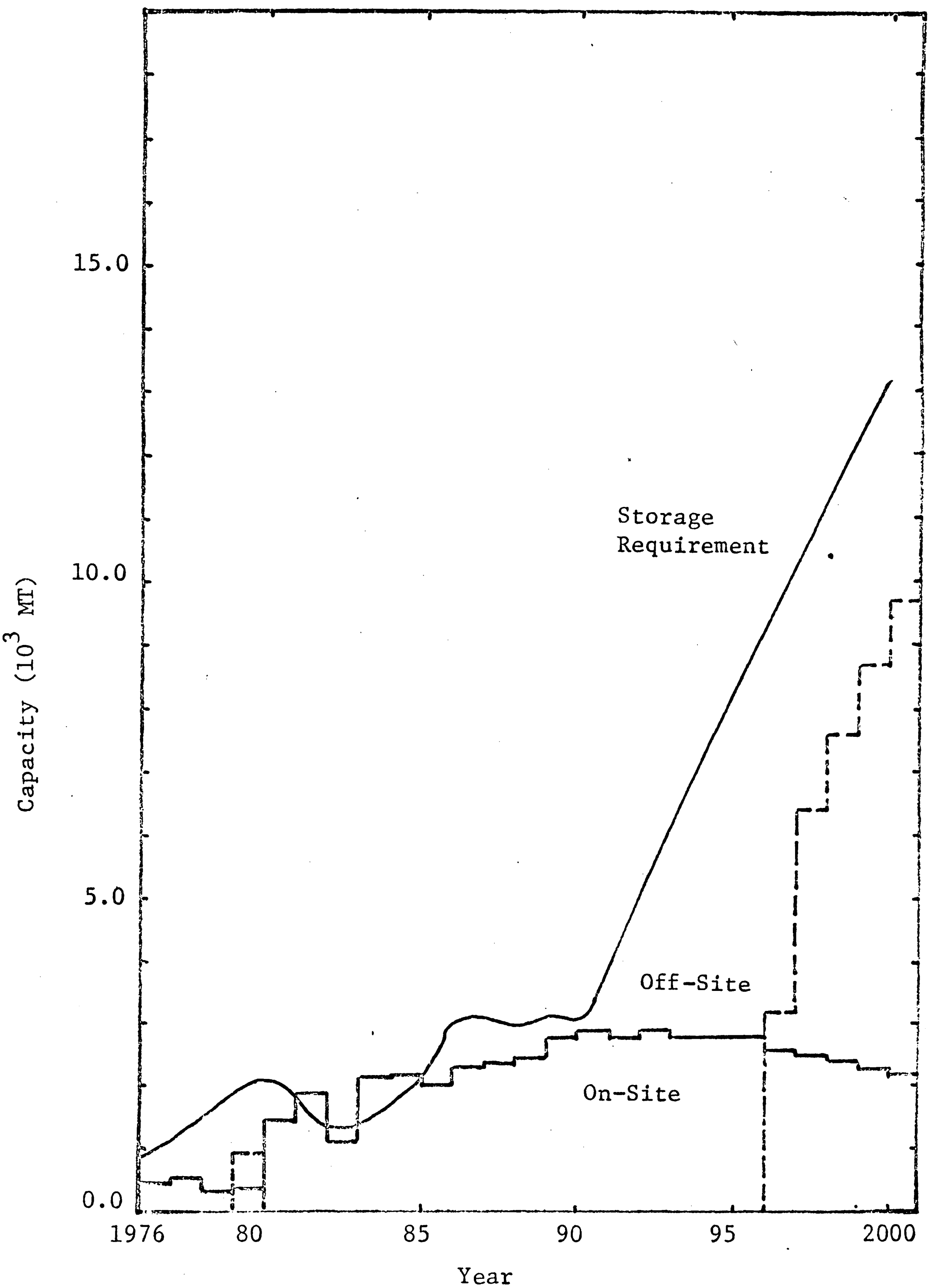


Figure 7.37. On-Site and Off-Site Storage Capacity Growth - Realistic Reprocessing Scenario, M = 1.5.

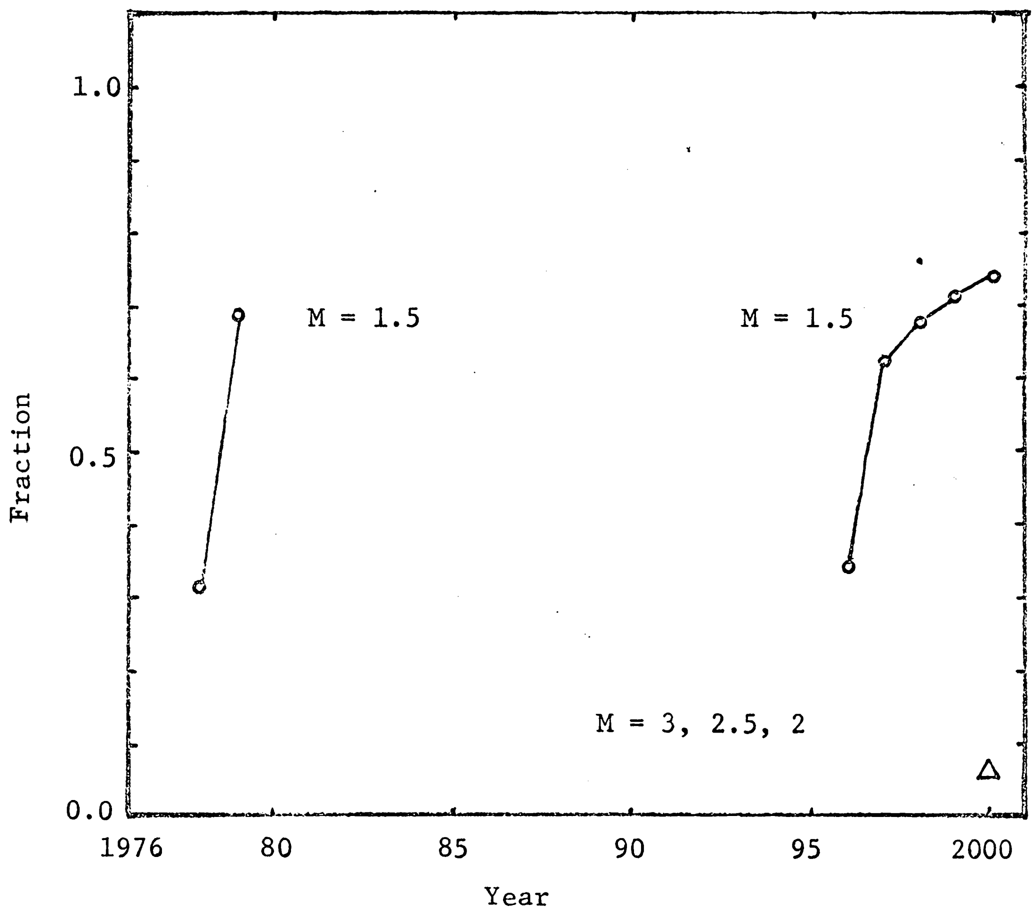


Figure 7.38. Fraction of Spent Fuel Transferred Off-Site - Realistic Reprocessing Scenario.

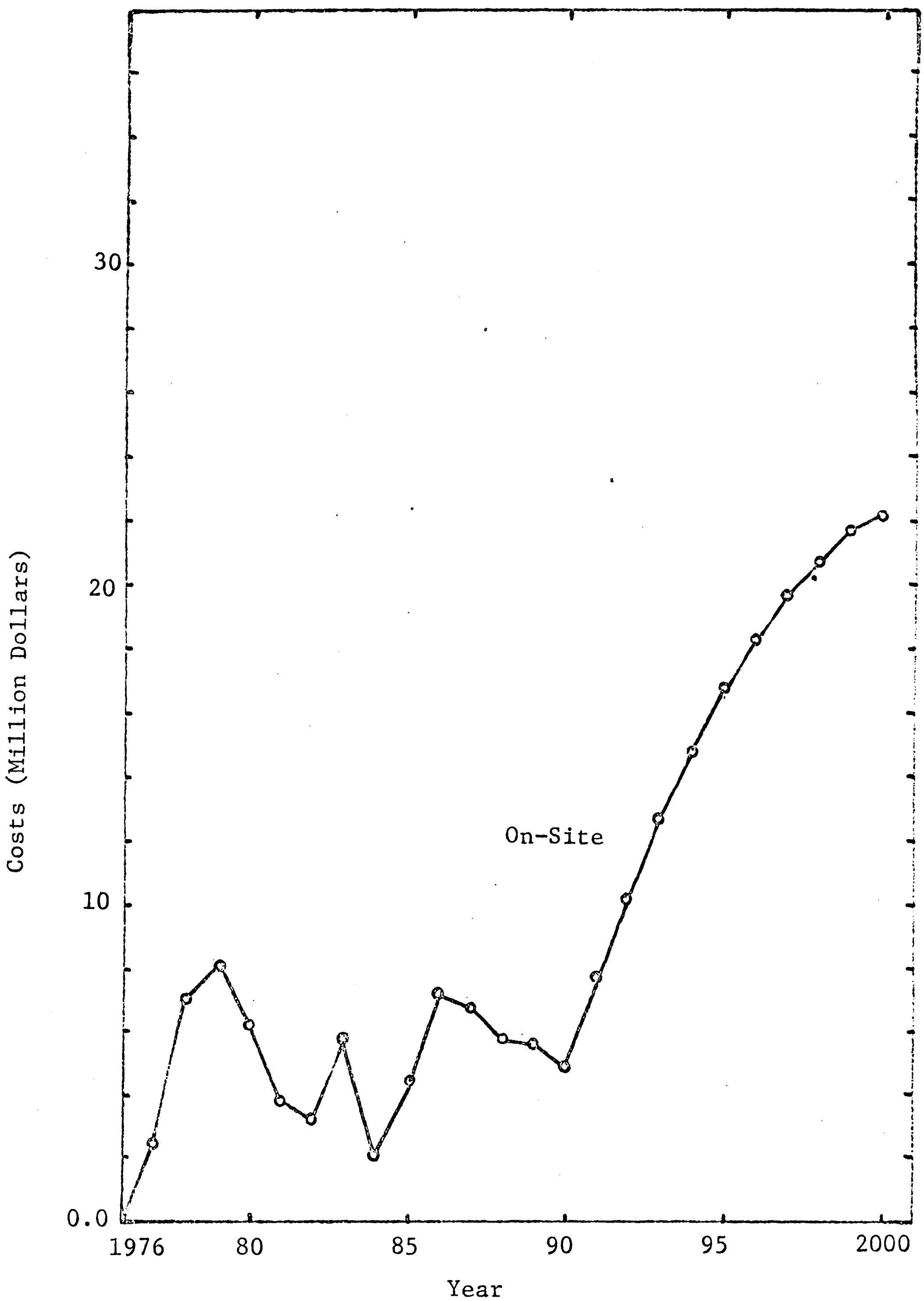


Figure 7.39. On-Site and Off-Site Storage Capacity Installation Costs - Realistic Reprocessing Scenario, Unconstrained Case.

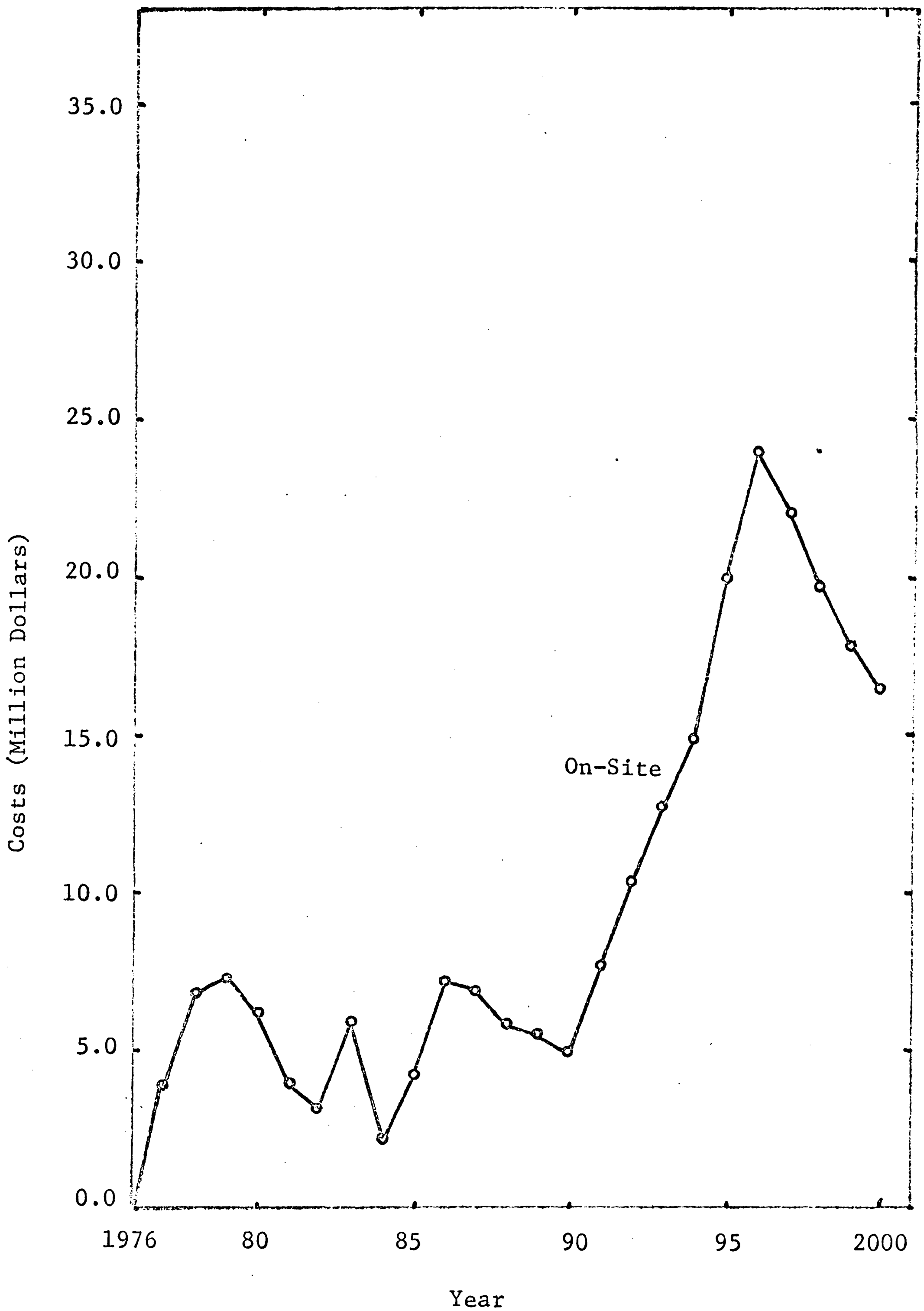


Figure 7.40. On-Site and Off-Site Storage Capacity Installation Costs - Realistic Reprocessing Scenario, M = 3.

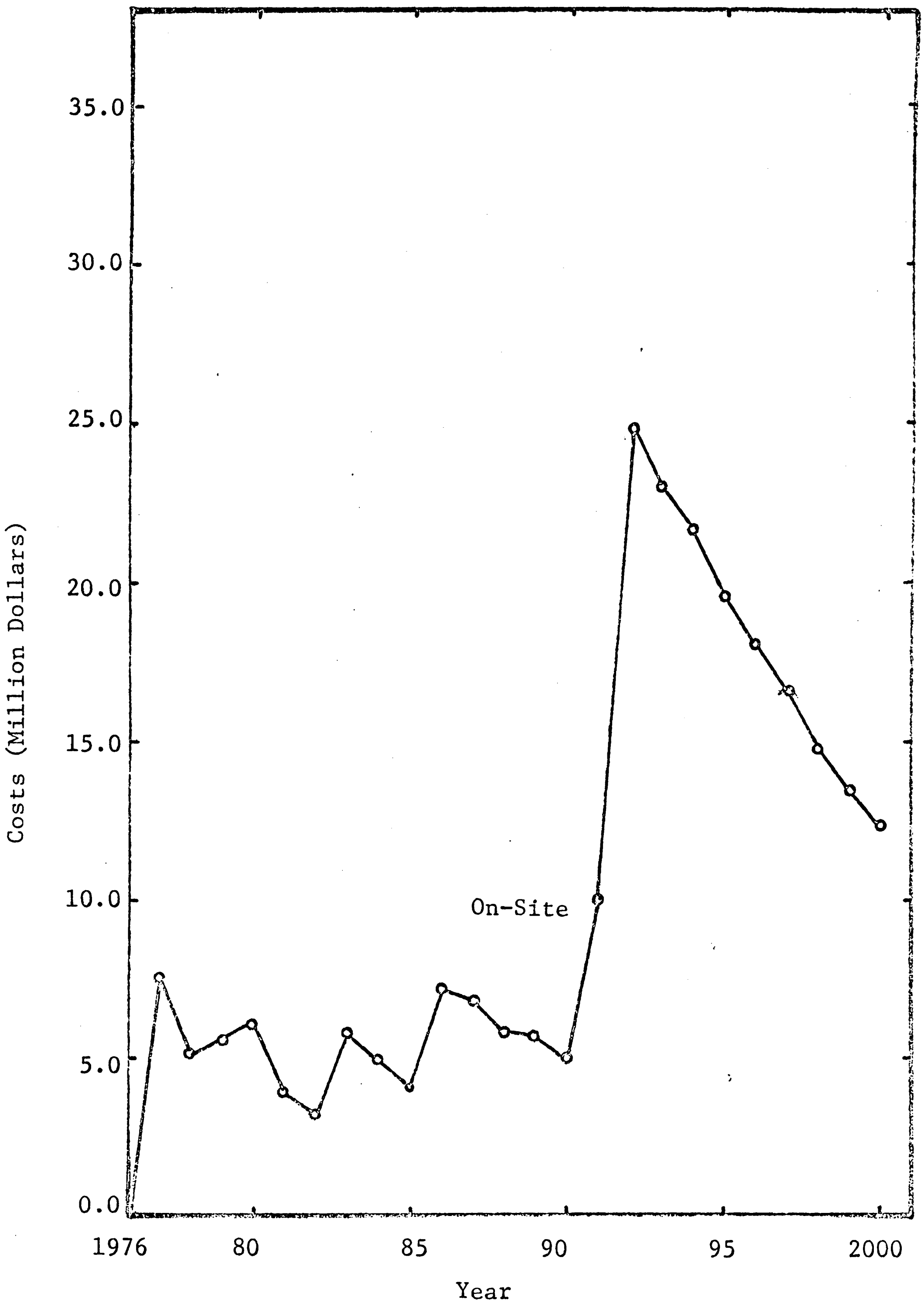


Figure 7.41. On-Site and Off-Site Storage Capacity Installation Costs - Realistic Reprocessing Scenario, M = 2.5.

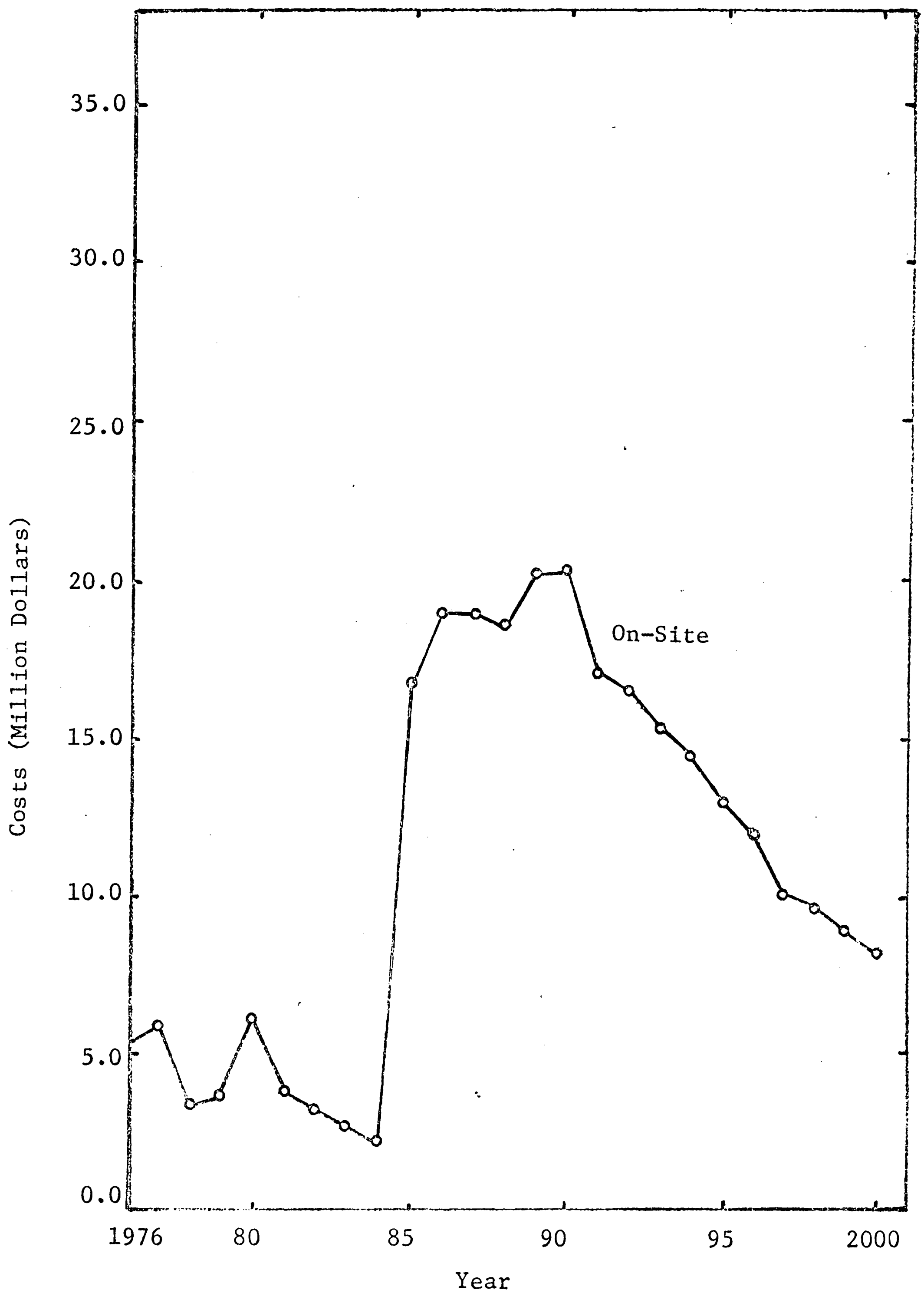


Figure 7.42. On-Site and Off-Site Storage Capacity Installation Costs - Realistic Reprocessing Scenario, M = 2.

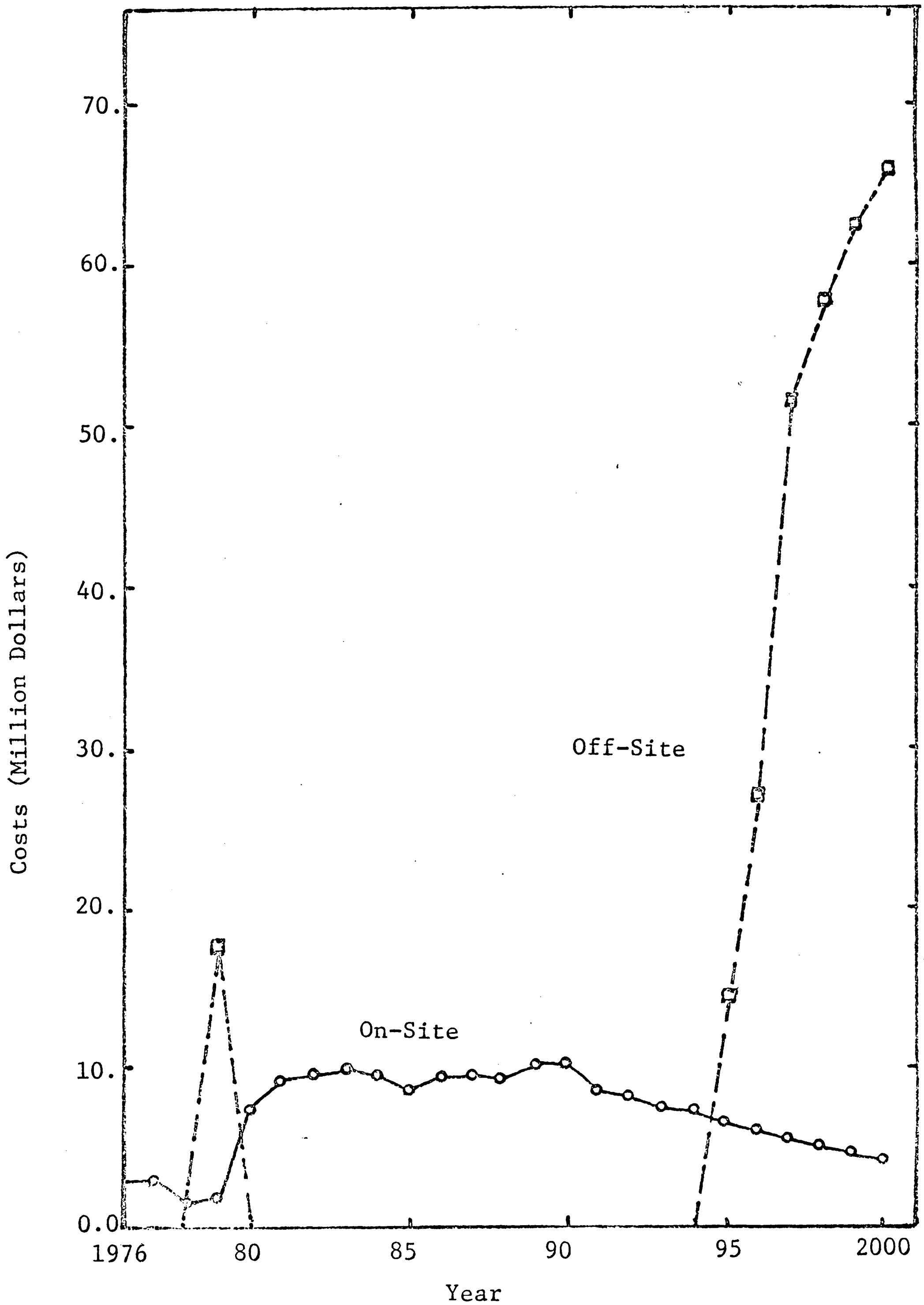


Figure 7.43. On-Site and Off-Site Storage Capacity Installation Costs, Realistic Reprocessing Scenario, M = 1.5.

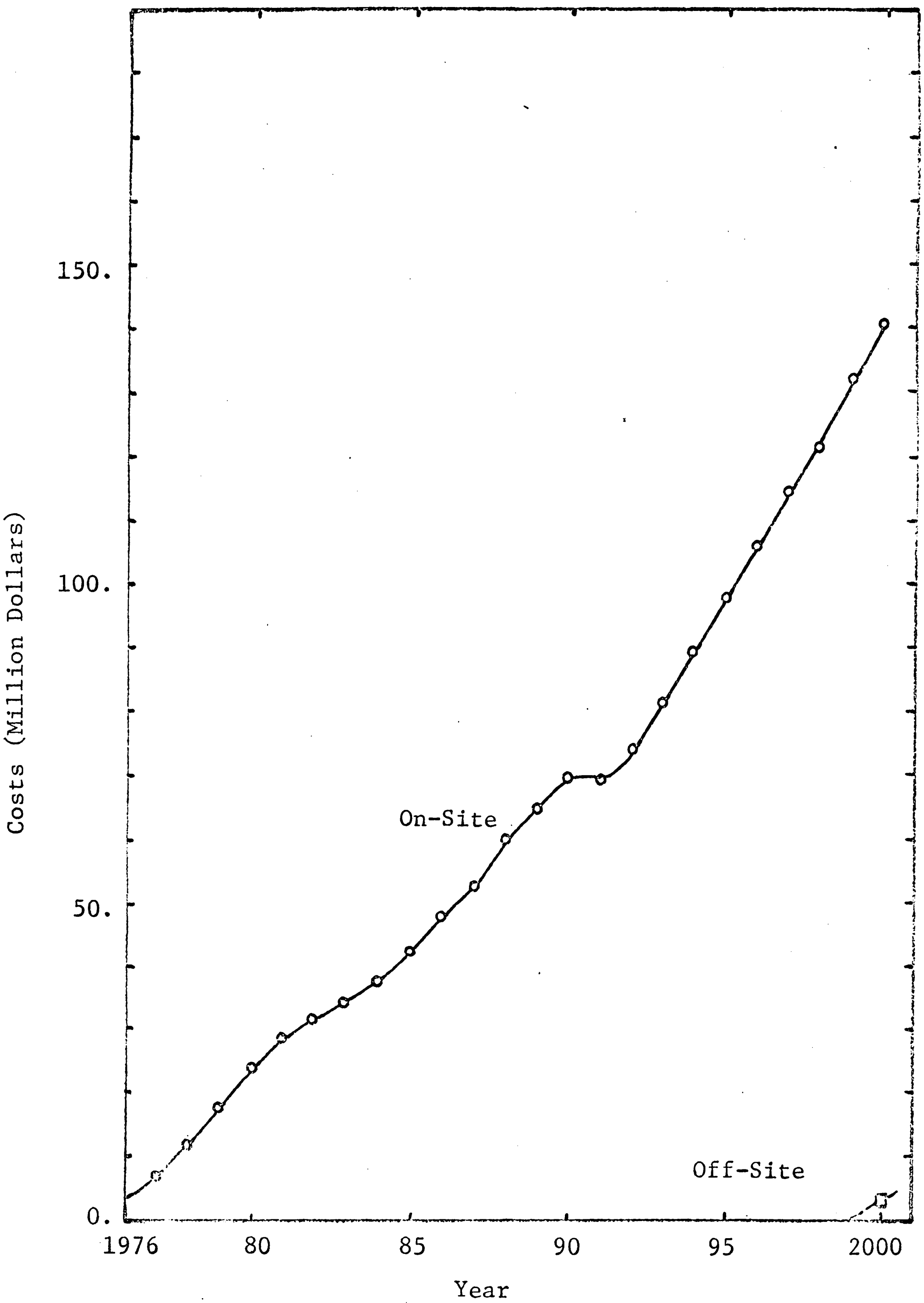


Figure 7.44. On-Site and Off-Site Spent Fuel Storage Costs - Realistic Reprocessing Scenario, M = ∞, 3, 2.5, 2.

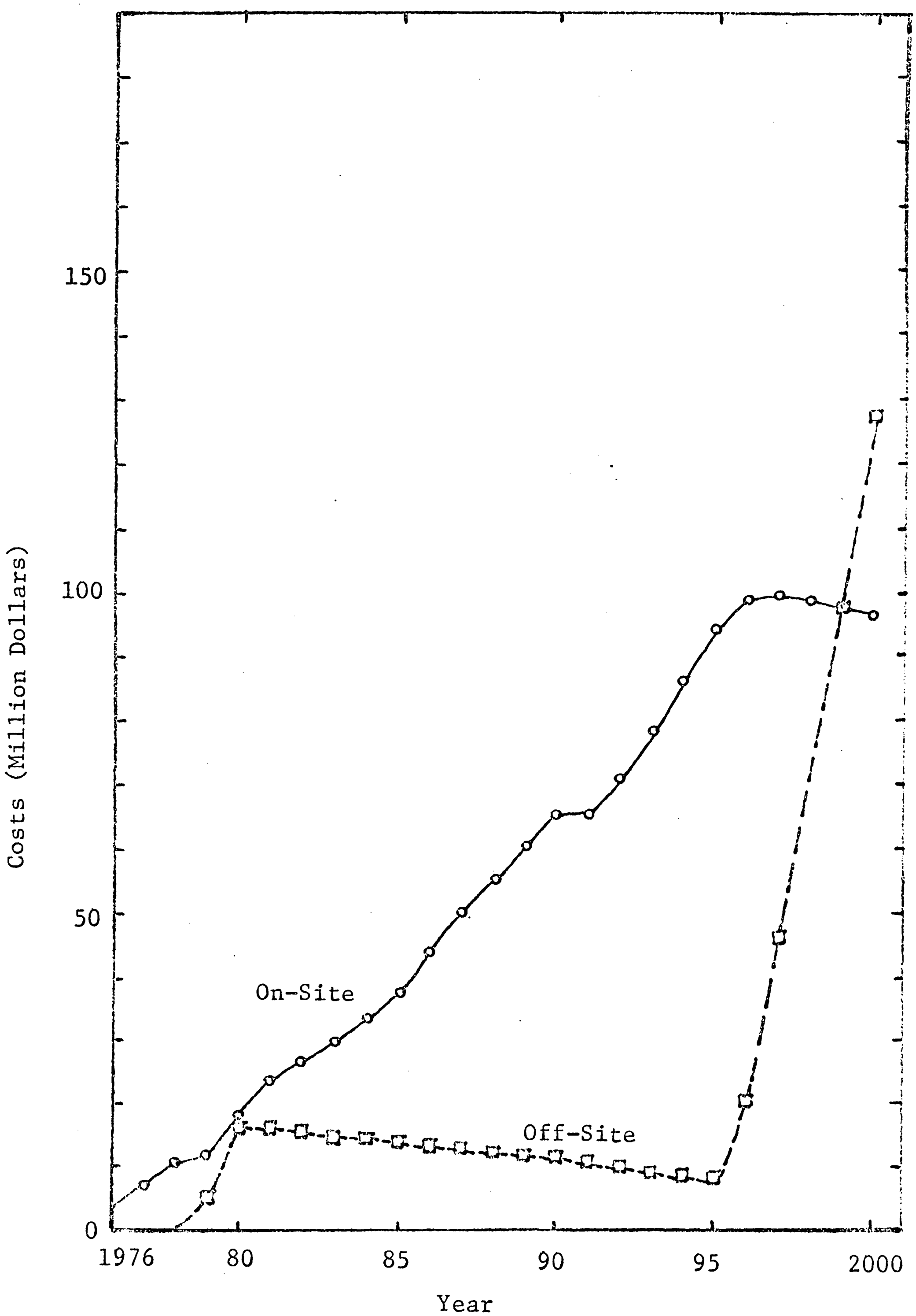


Figure 7.45. On-Site and Off-Site Spent Fuel Storage Costs - Realistic Reprocessing Scenario, M = 1.5.

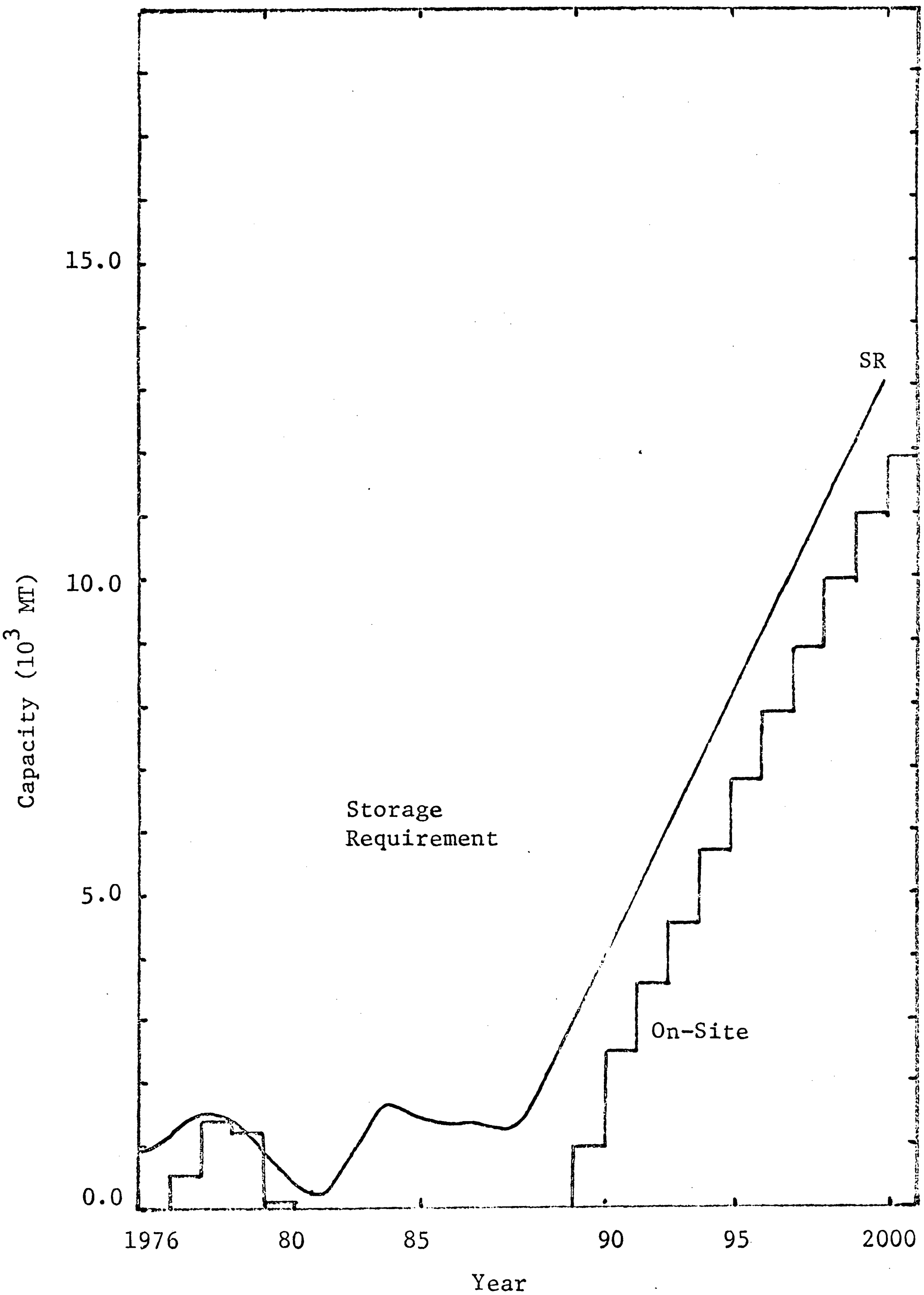


Figure 7.46. On-Site and Off-Site Storage Capacity Growth - Optimistic Reprocessing Scenario, Unconstrained Case.

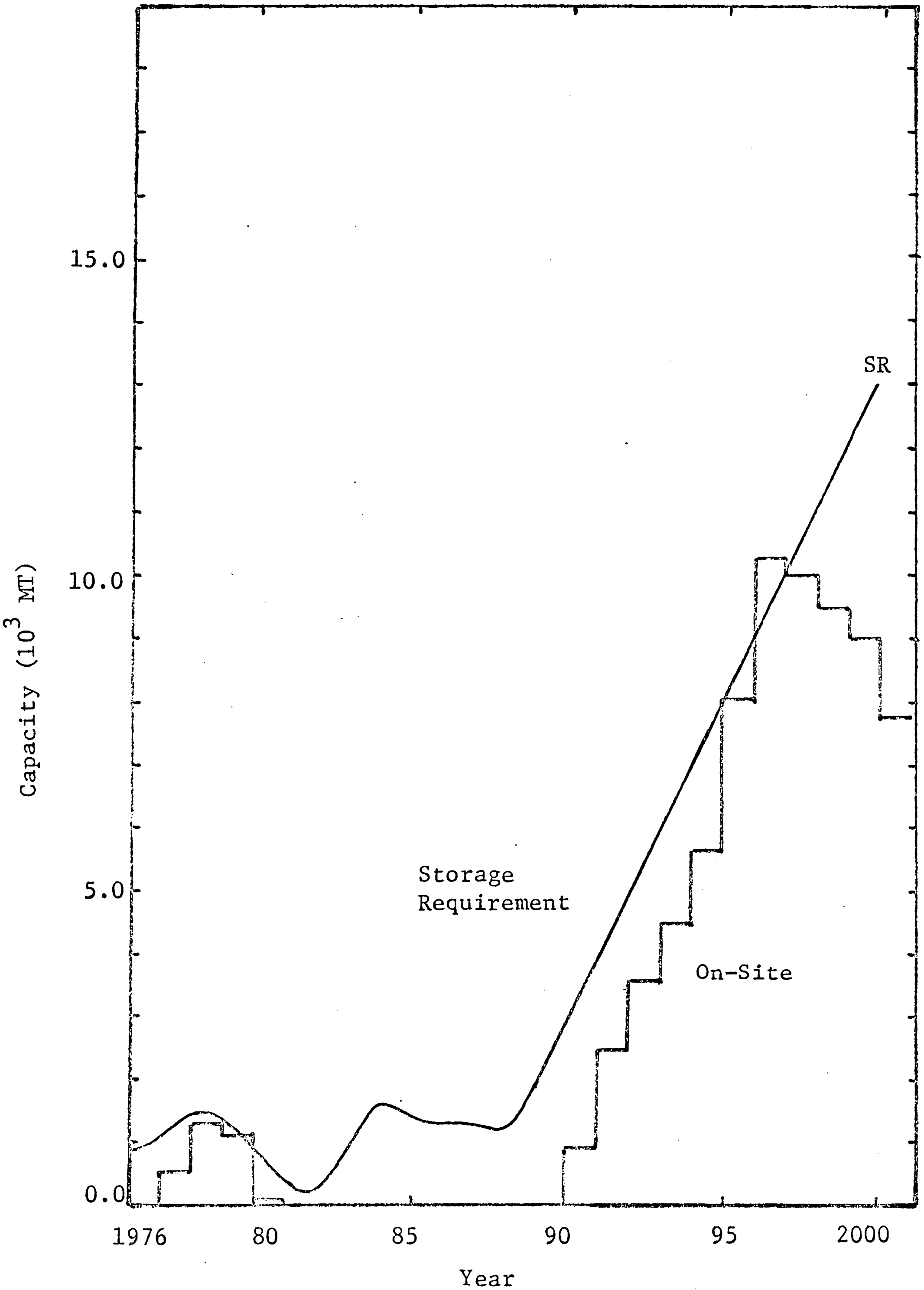


Figure 7.47. On-Site and Off-Site Storage Capacity Growth - Optimistic Reprocessing Scenario, M = 3.

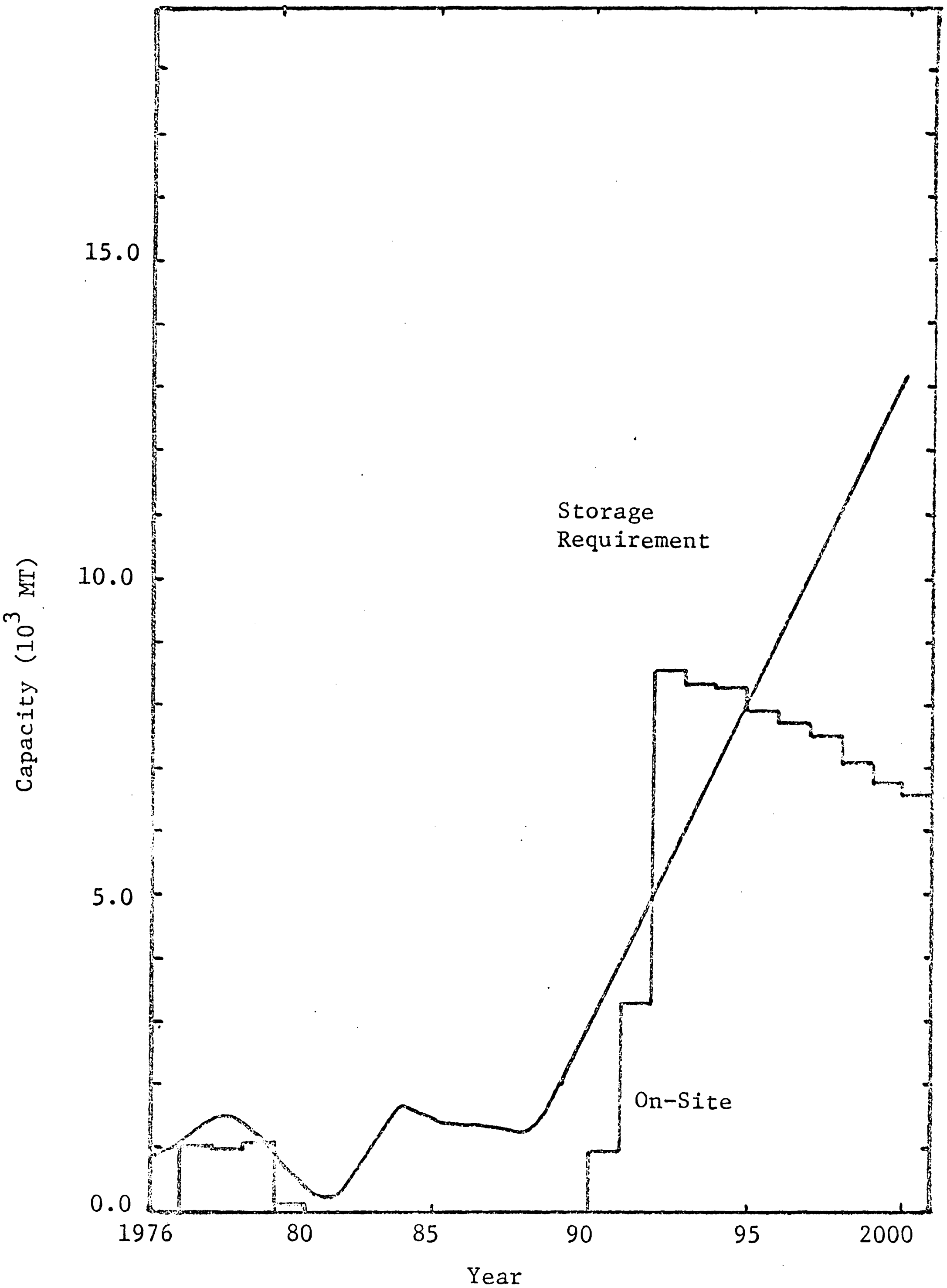


Figure 7.48. On-Site and Off-Site Storage Capacity Growth - Optimistic Reprocessing Scenario, M = 2.5.

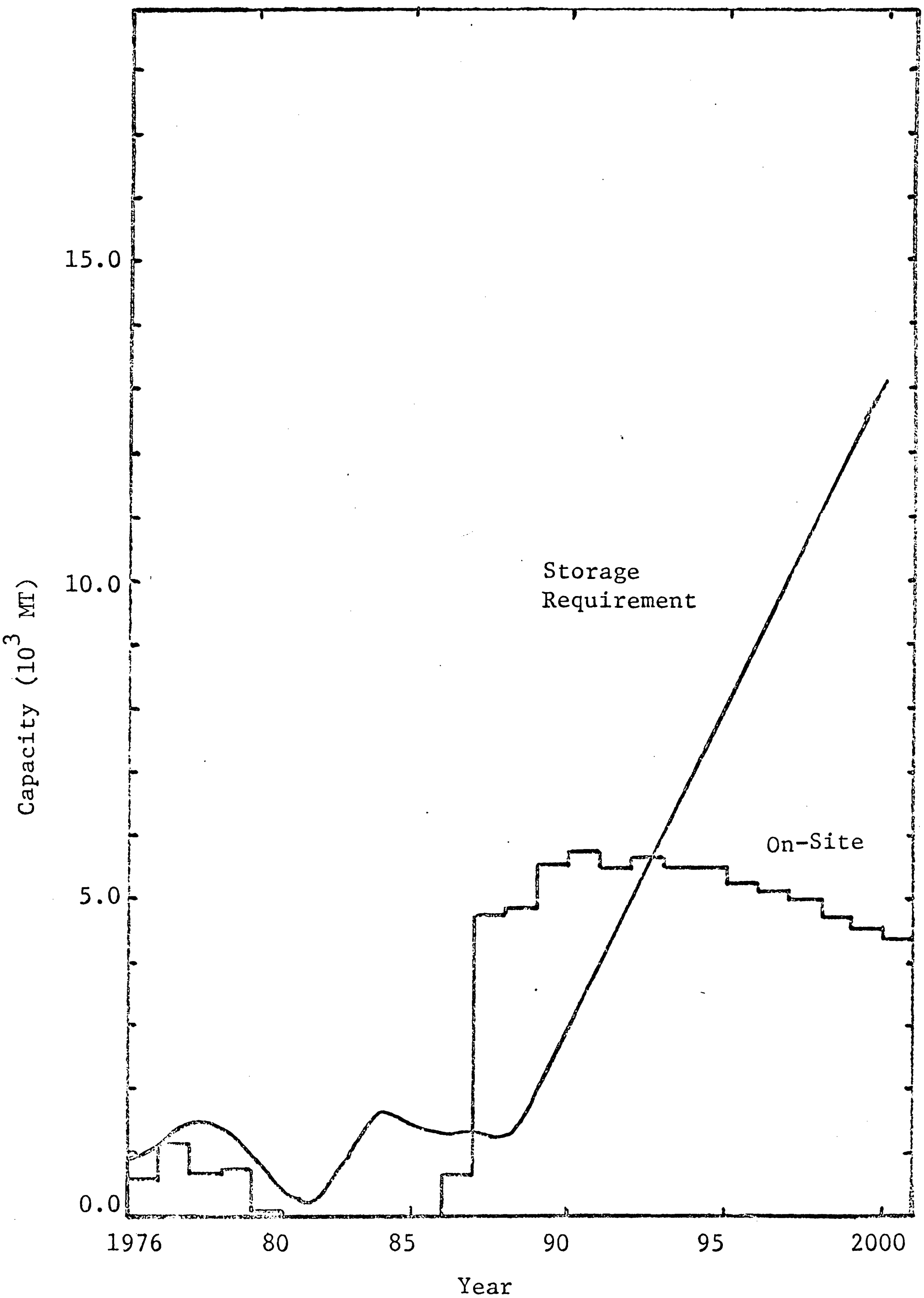


Figure 7.49. On-Site and Off-Site Storage Capacity Growth - Optimistic Reprocessing Scenario, M = 2.

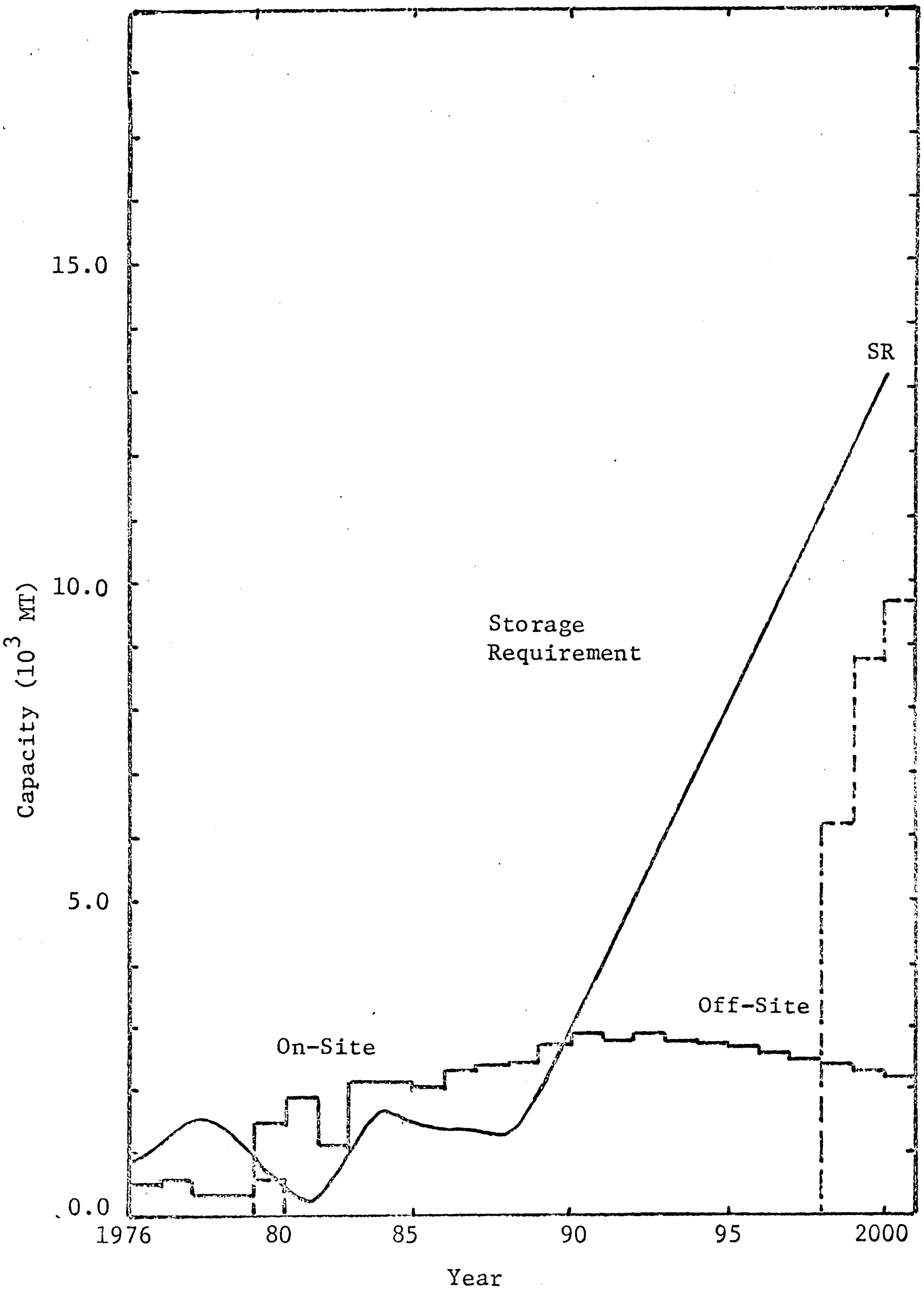


Figure 7.50. On-Site and Off-Site Storage Capacity Growth
- Optimistic Reprocessing Scenario, M = 1.5.

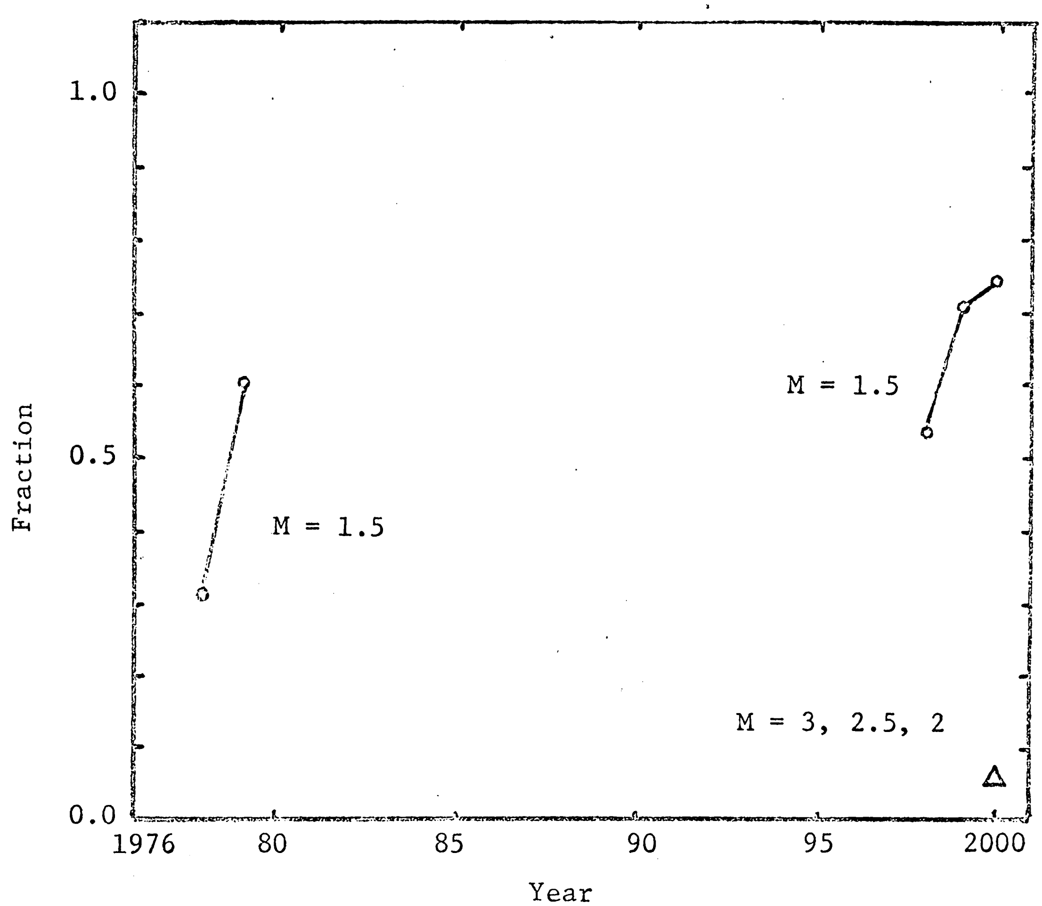


Figure 7.51. Fraction of Spent Fuel Transferred Off-Site - Optimistic Reprocessing Scenario.

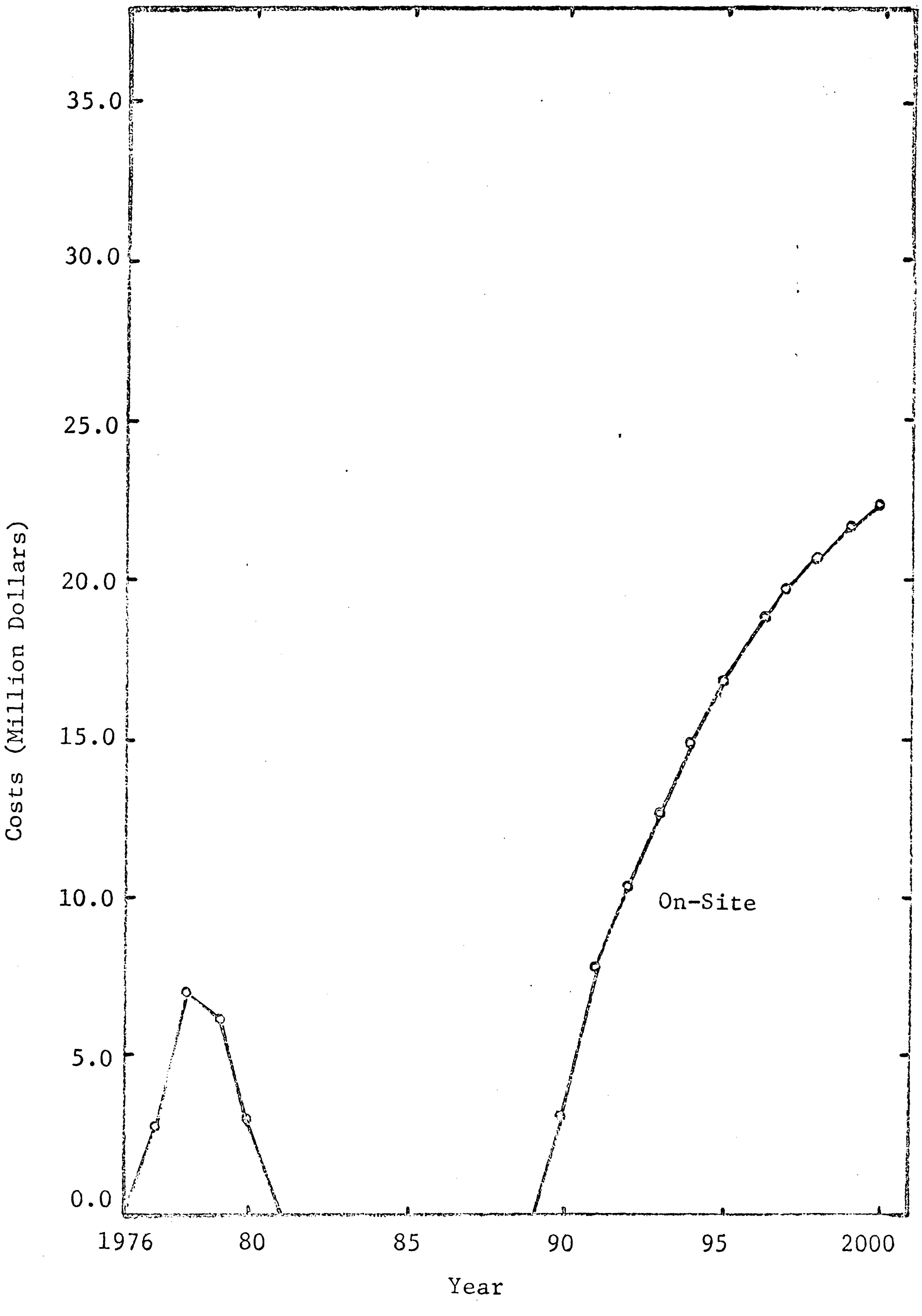


Figure 7.52. On-Site and Off-Site Storage Capacity Installation Costs - Optimistic Reprocessing Scenario, Unconstrained Case.

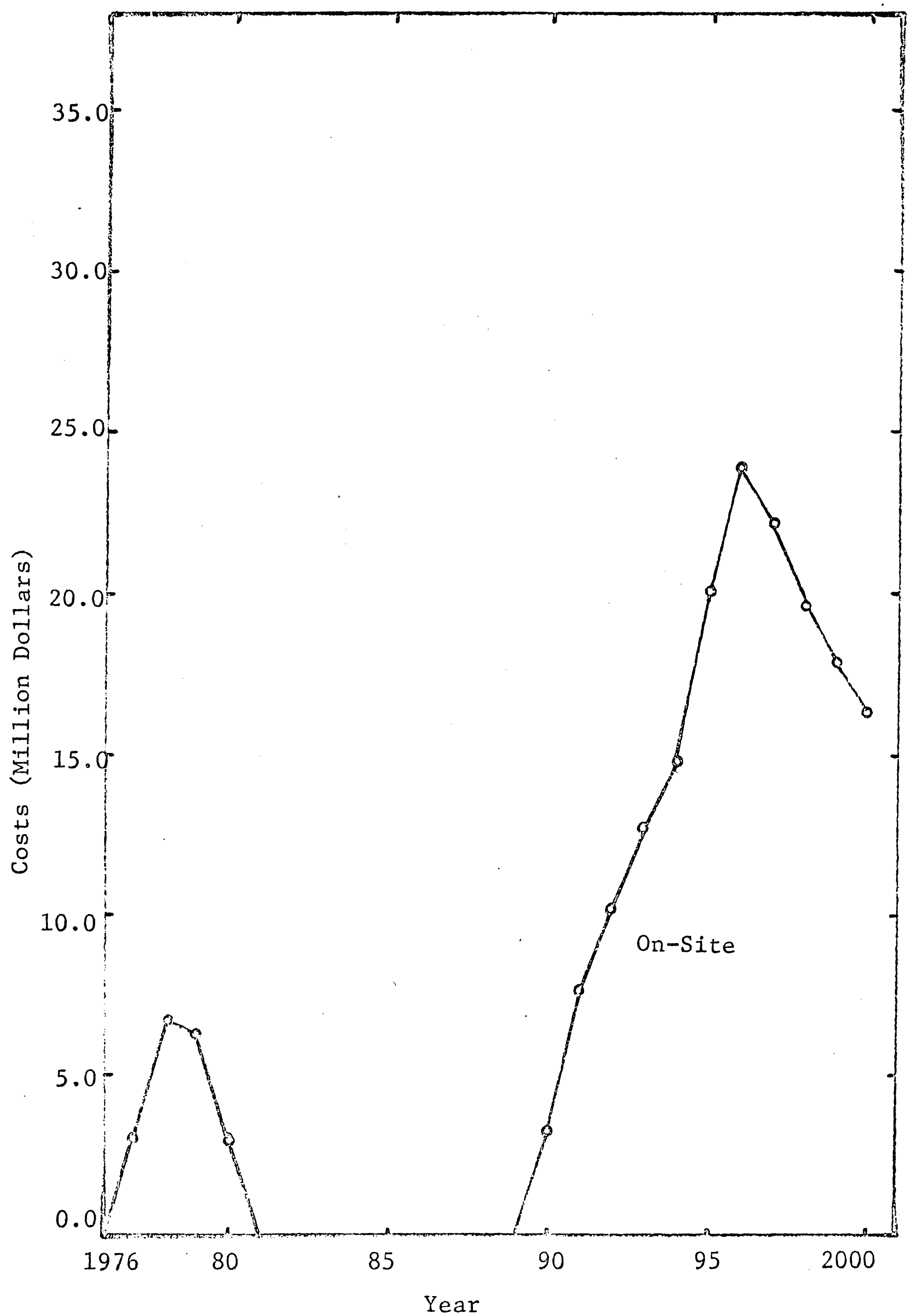


Figure 7.53. On-Site and Off-Site Storage Capacity Installation Costs - Optimistic Reprocessing Scenario, M = 3.

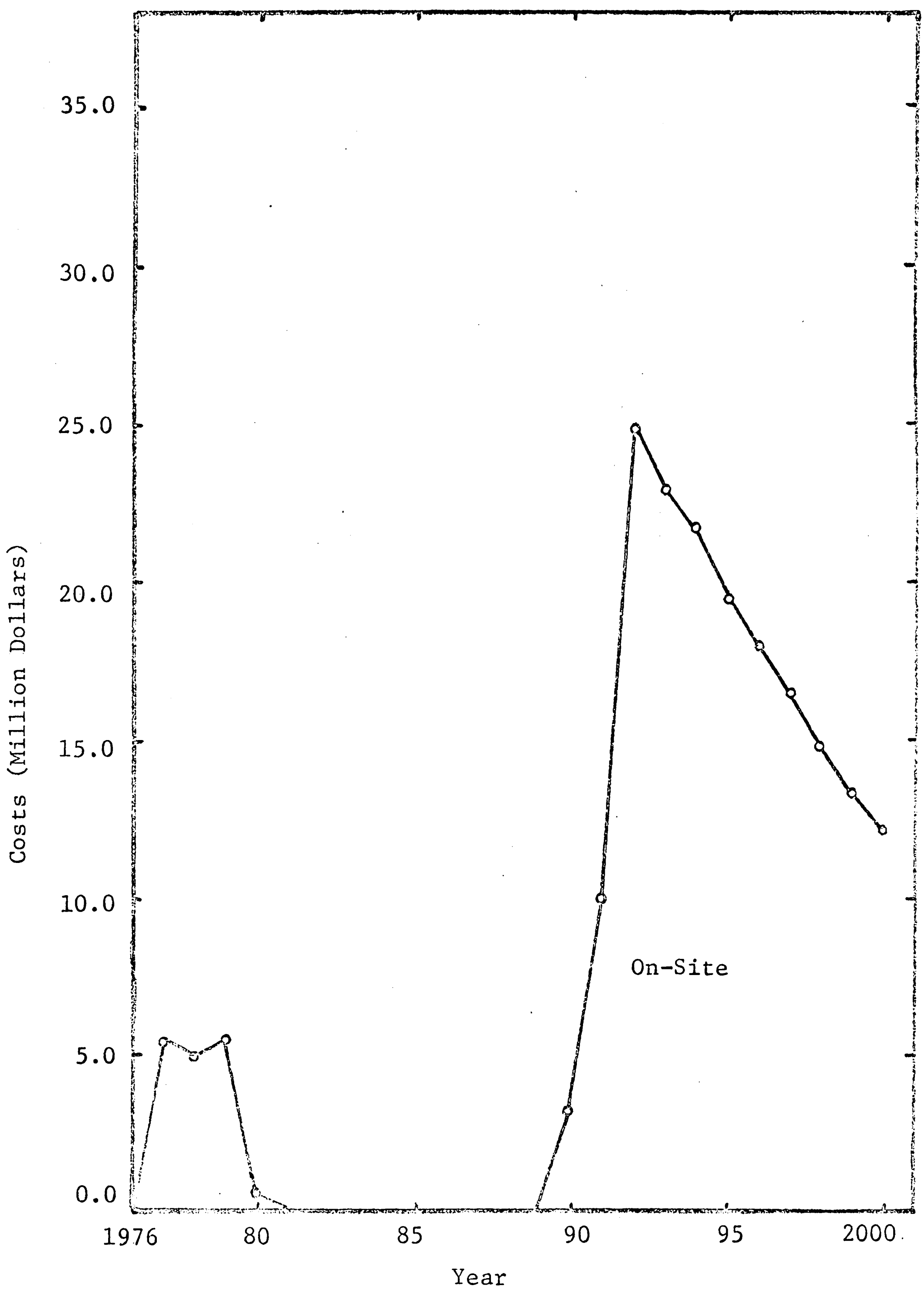


Figure 7.54. On-Site and Off-Site Storage Capacity Installation Costs - Optimistic Reprocessing Scenario, M = 2.5.

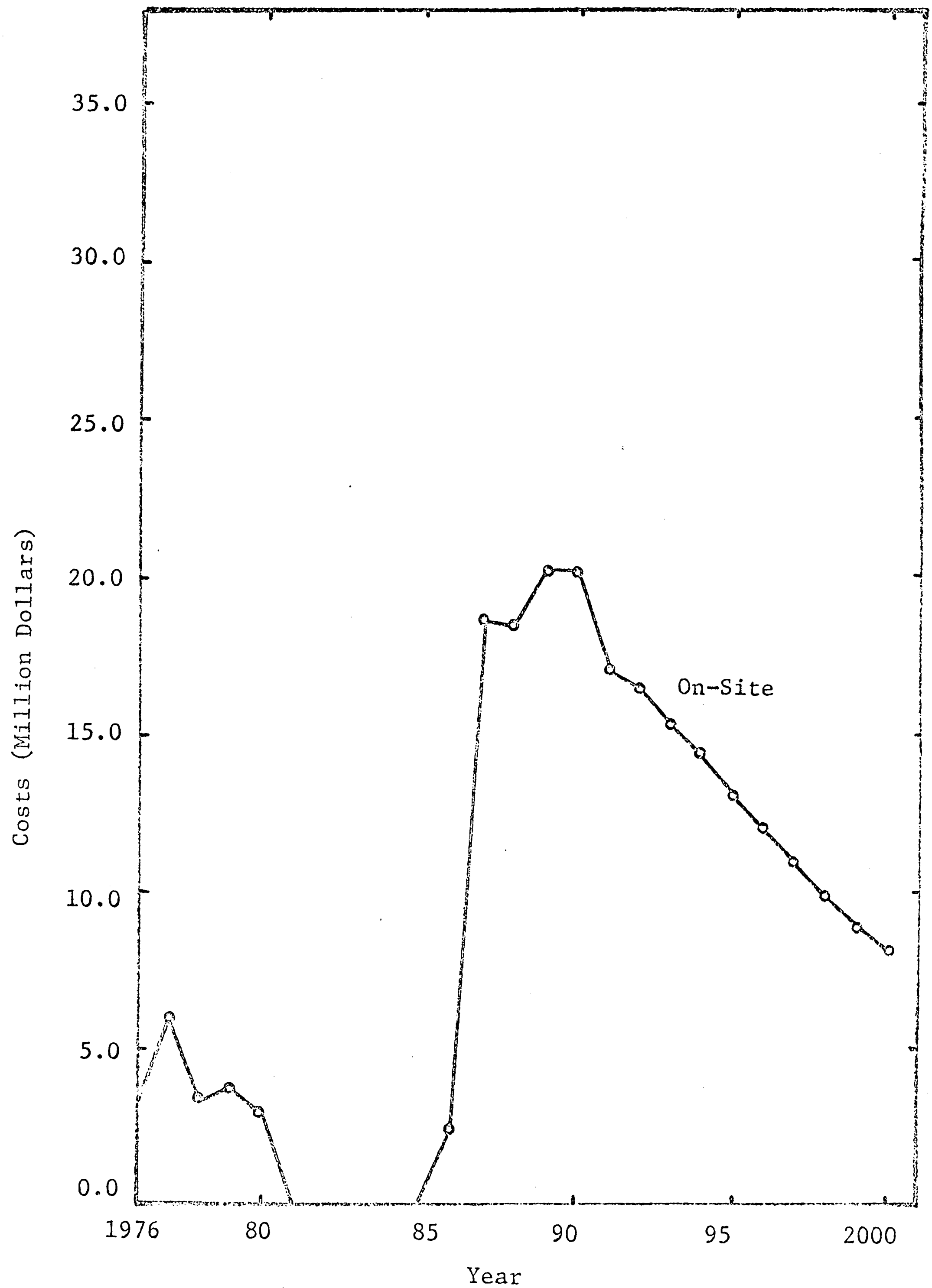


Figure 7.55. On-Site and Off-Site Storage Capacity Installation Costs - Optimistic Reprocessing Scenario, M = 2.

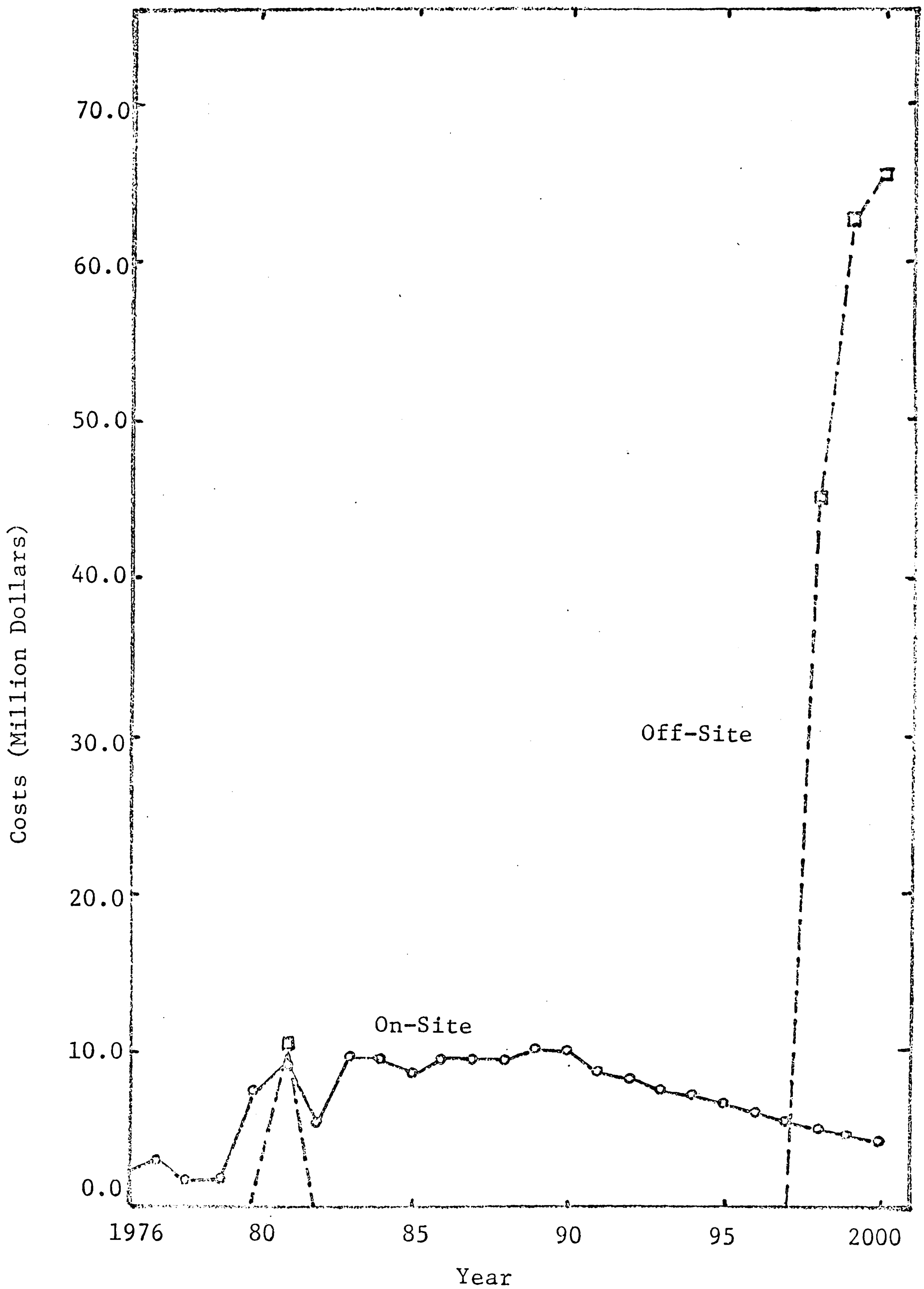


Figure 7.56. On-Site and Off-Site Storage Capacity Installation Costs - Optimistic Reprocessing Scenario, M = 1.5.

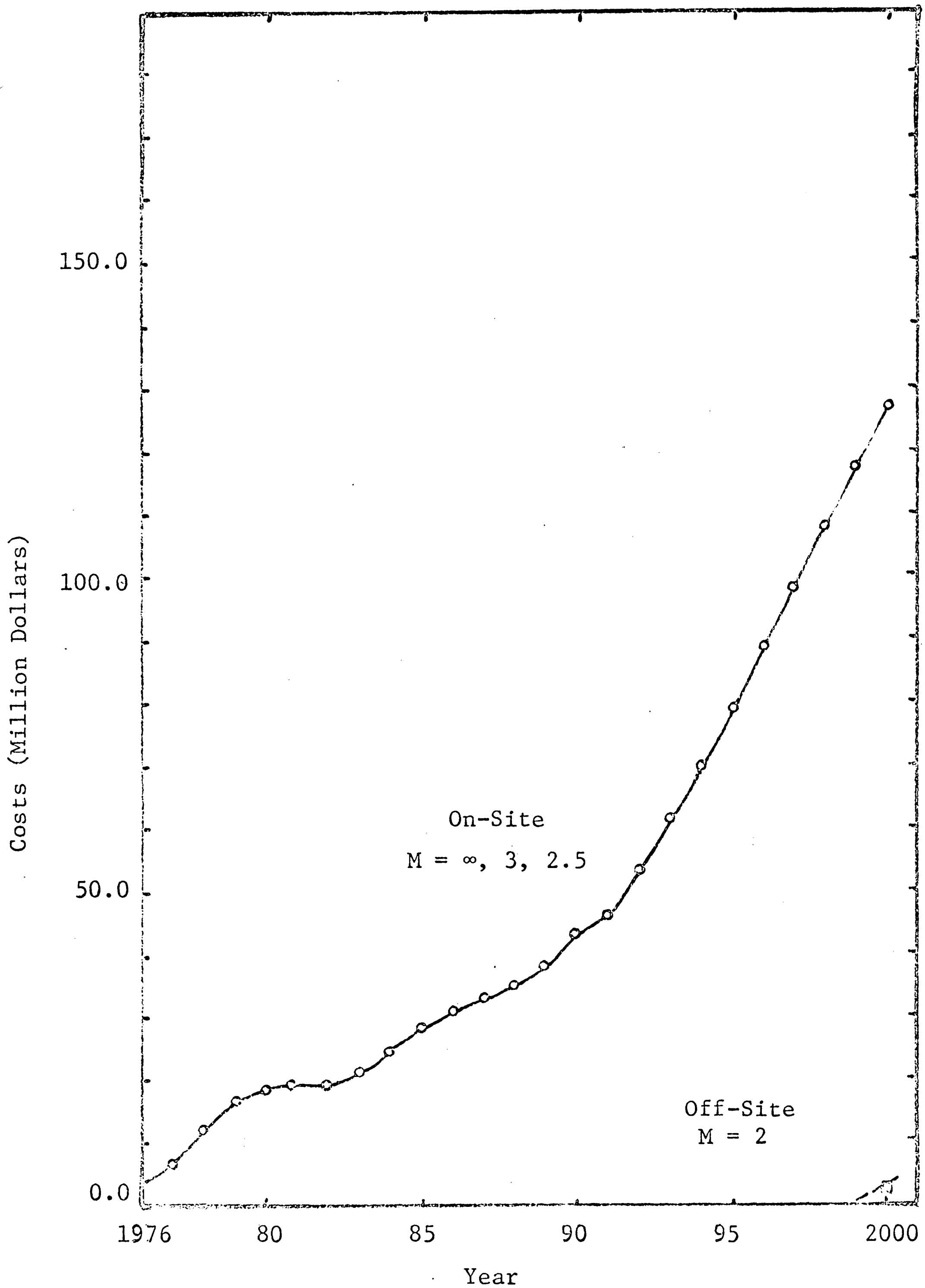


Figure 7.57. On-Site and Off-Site Spent Fuel Storage Costs - Optimistic Reprocessing Scenario.

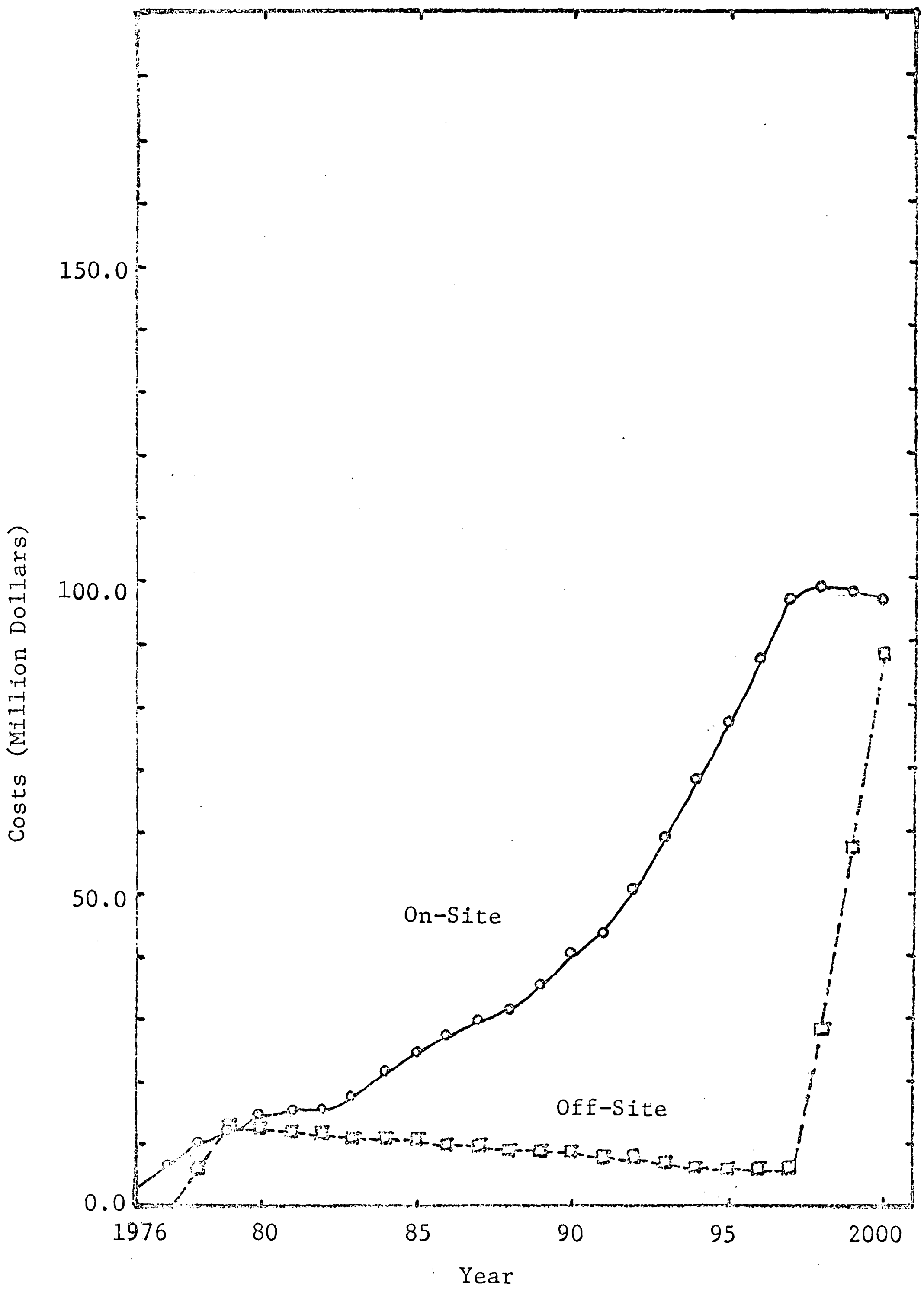


Figure 7.58. On-Site and Off-Site Storage Costs
- Optimistic Reprocessing, M = 1.5.

8. CONCLUSIONS

The linear spent-fuel storage model developed in this study demonstrated that careful storage capacity expansion planning is necessary in order to satisfy spent-fuel storage requirements in the future at the minimum cost.

The parameters of the model were selected so that the model structure implied coupling of the off-site storage facilities with the reprocessing plants.

Table 8.1 and Figure 8.1 display the total cost of the storage capacity expansion programs under the studied demand situations and the on-site capacity expansion restrictions. Since acquisition of the additional on-site storage can be accomplished in a most economical way by redesigning the physical dimensions of future reactors and/or installation of racks with closer spacing, the restrictions on the on-site capacity expansion were linked to the predicted growth rate of nuclear reactor installation. The results for the expansion factor denoted by $M = \infty$ apply to unconstrained on-site and off-site expansion. Also, in this case, the connection between capacity expansion and the future reactor installation is decoupled. It should be pointed out that the results indicate an increase in the storage expansion program if the new reactor storage pool expansion is restricted. For instance, if expansion of the pool capacity of the reactors installed after 1976 were possible only by 50% ($M = 1.5$), in the zero demand case, the storage program cost would rise to about 6 billion dollars against 3.2 billion for

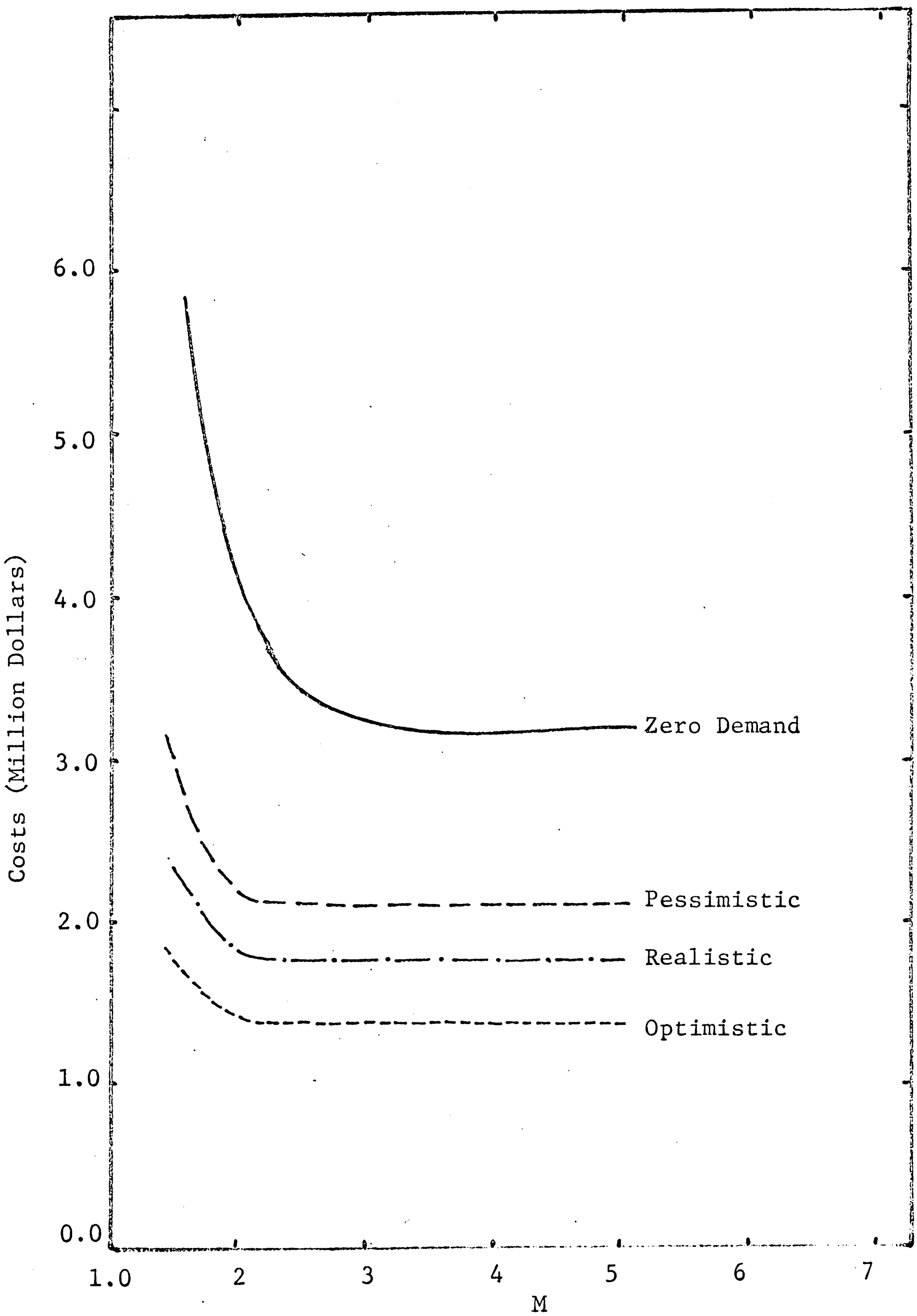


Figure 8.1. Total Cost of Spent—Fuel Storage.

Table 8.1. Total Cost of Spent-Fuel Storage

Scenario	Total Storage Program Cost [10^6 $]				
	M = ∞	M = 3	M = 2.5	M = 2	M = 1.5
ZD	3189.4	3243.0	3424.7	4271.7	6064.9
PR	2145.0	2147.2	2155.8	2194.4	2991.9
RR	1796.1	1798.1	1806.9	1838.5	2386.4
OR	1383.7	1385.8	1394.4	1423.9	1779.0

Legend: ZD = Zero demand

PR = Pessimistic reprocessing scenario (1979)

RR = Realistic reprocessing scenario (1981)

OR = Optimistic reprocessing scenario (1983) the unconstrained on-site capacity expansion case. This cost increase is due primarily to the necessary reliance on the more expensive off-site storage. A secondary effect on the cost increase is due to the fact that to a certain extent, it is more economical to overbuild the on-site capacity above the current spent-fuel storage requirements than to build an off-site storage facility. This cost increase is caused by a penalty for carrying the unused capacity from one period to the next. This penalty is introduced into the model by use of the present worth cost concept (discounting) and the model requirement that storage needs must be met at all times.

The storage program cost breakdown into individual cost components for the studied scenarios is displayed in Table 8.2 through Table 8.5. The trend indicating the decrease in the program storage costs with reduction of the delay of the reprocessing activity start-up was expected; and, thus, contributes to the validation of the model.

The present worth of the profit realized by spent-fuel reprocessing and recycling of the recovered fuel as a function of timing of the reprocessing activity is shown in Table 8.6 and Figure 8.2. The results indicate that a prompt solution of the plutonium recycle issue and resumption of the spent fuel reprocessing would result in substantial savings. For instance, delay of the reprocessing start-up of about four years from 1979 to 1983 would result in a loss of about 1.2 billion dollars. This quantity represents about 40% of revenues realized by the reprocessing program which would start in 1979. Loss in revenues due to fissile plutonium-241 decay would amount to approximately 9 million dollars. Since expenditures for spent-fuel storage

Table 8.2. Spent-Fuel Storage Cost Breakdown

- Zero Demand Case

Constraint	Cost component [10^6 \$]						Total
	c_1	c_2	c_3	c_4	c_5	c_6	
$M = \infty$	482.4	--	--	--	2,707.	--	3189.4
M = 3	534.1	--	--	--	2,706.	2.6	3242.7
M = 2.5	512.6	137.5	--	--	2,671.	103.6	3424.7
M = 2	341.8	561.9	--	--	2,352.	1016.0	4271.7
M = 1.5	170.9	1120.0	--	--	1594.0	3180.0	6064.9

Legend: c_1 = Total on-site capacity installation costs [\$$10^6$]

c_2 = Total off-site capacity installation costs

c_3 = Total on-site handling costs

c_4 = Total off-site handling and transportation costs

c_5 = Total on-site spent fuel storage costs

c_6 = Total off-site spent fuel storage costs

Table 8.3. Spent-Fuel Storage Cost Breakdown

- Pessimistic Reprocessing Scenario

Constraint	Cost component [10^6 $]						Total
	c_1	c_2	c_3	c_4	c_5	c_6	
M = ∞	279.0	--	--	--	1,866	0.0	2145.
M = 3	279.6	--	--	--	1,865	2.6	2147.2
M = 2.5	288.2	--	--	--	1,865	2.6	2155.8
M = 2	326.8	--	--	--	1,865	2.6	2194.4
M = 1.5	70.9	388.5	--	--	1,561	871.5	2991.9

Table 8.4. Spent-Fuel Storage Cost Breakdown

- Realistic Reprocessing Scenario

Constraint	Cost component [10^6 $]						Total
	c_1	c_2	c_3	c_4	c_5	c_6	
M = ∞	233.1	--	--	--	1563.	--	1796.1
M = 3	233.7	--	--	--	1562.	2.6	1998.2
M = 2.5	242.3	--	--	--	1562.	2.6	1806.9
M = 2	273.9	--	--	--	1562.0	2.6	1838.5
M = 1.5	170.9	281.7	--	--	1363	570.8	2386.4

Table 8.5. Spent-Fuel Storage Cost Breakdown

- Optimistic Reprocessing Scenario

Constraint	Cost component [10^6 \$]						Total
	c_1	c_2	c_3	c_4	c_5	c_6	
M = ∞	184.7	--	--	--	1,199	0.0	1383.7
M = 3	185.2	--	--	--	1,198	2.6	1385.8
M = 2.5	193.8	--	--	--	1,198	2.6	1394.4
M = 2	223.3	--	--	--	1,198	2.6	1423.9
M = 1.5	170.9	184.4	--	--	1,077	346.7	1779.0

Table 8.6. Profit from the Reprocessing of Spent Fuel

Year	Profit [10^6 $]			
	NR	OP	RR	PR
1976	--	--	--	--
1977	--	--	--	--
1978	--	--	--	--
1979	--	17.25	--	--
1980	--	71.87	--	--
1981	--	121.9	24.38	--
1982	--	147.2	73.60	--
1983	--	147.0	122.5	24.50
1984	--	145.4	145.4	72.7
1985	--	190.5	142.9	119.
1986	--	226.1	127.2	127.2
1987	--	239.	151.	113.2
1988	--	257.8	179.3	100.9
1989	--	229.0	189.1	119.5
1990	--	203.0	203.4	141.5
1991	--	183.	183.	151.1
1992	--	164.	164.5	164.2
1993	--	147.9	147.9	147.9
1994	--	133.0	133.0	133.0
1995	--	119.6	119.6	119.6
1996	--	105.6	105.6	105.6
1997	--	93.24	93.24	93.25
1998	--	82.23	82.23	82.23
1999	--	72.45	72.45	72.45
2000	--	63.77	63.77	63.77
Total profit	--	3162.	2524.	1952.2
Total Pu 241 decay loss	--	8.36	8.89	9.48

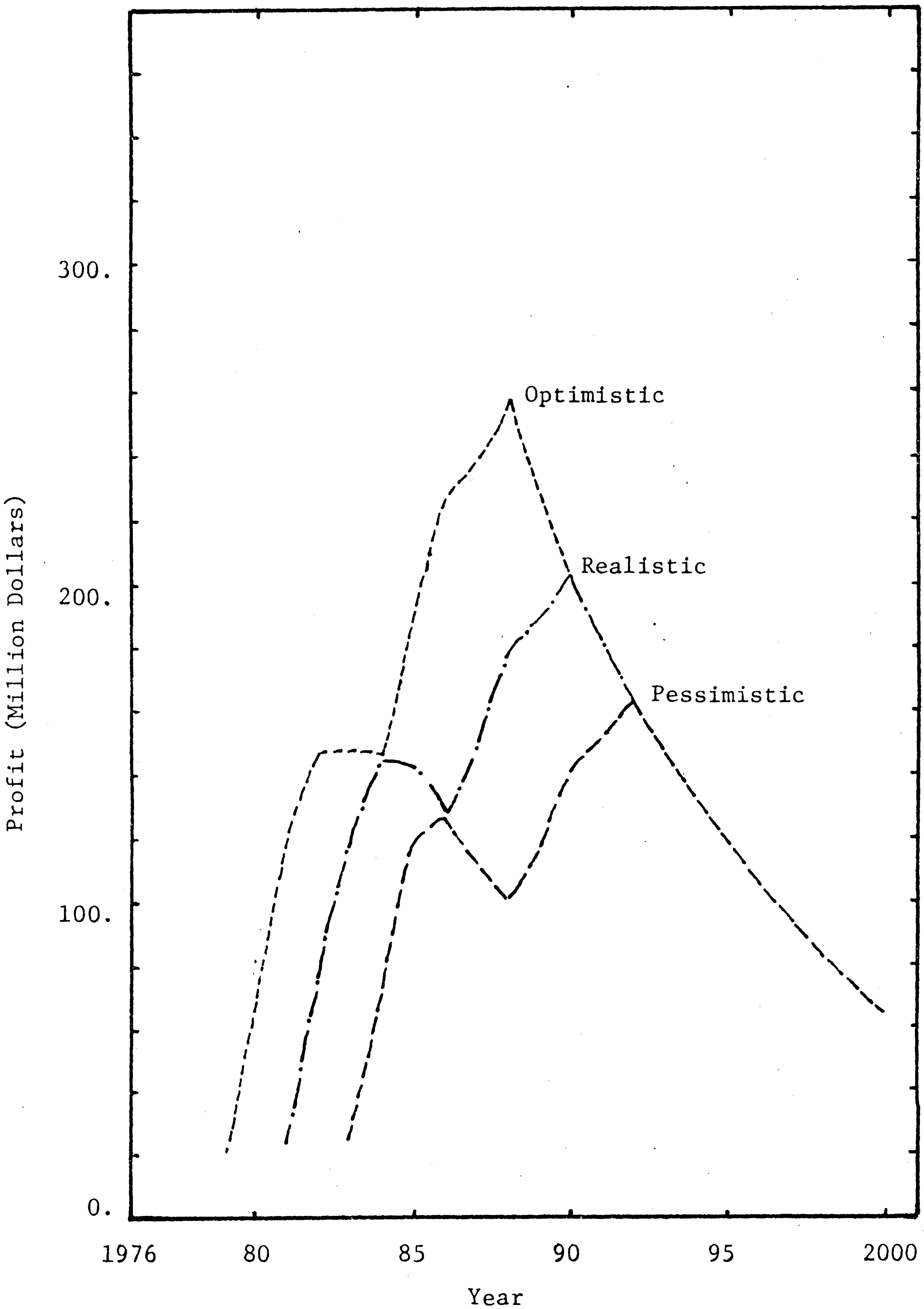


Figure 8.2. Profit from Recycled Fuel.

will occur concurrently with the revenues from plutonium and uranium recycle, the overall economic balance of the back end of the fuel cycle was estimated. The comparison between the scenarios is exhibited in Table 8.7. The results indicate that for delayed reprocessing start-up to 1983 with inadequate reprocessing capability, the spent-fuel storage costs will exceed the profit realized by the nuclear fuel recycle. Consequently, in this case, the back end of the fuel cycle would become a liability with the net result that there is an increased cost to the fuel cycle. Figure 8.3 shows that the back end of the fuel cycle, with the currently planned total reprocessing program reaching about 5750 MT of annual capacity, would break even if the reprocessing activity were resumed about in mid-1982.

The purpose of the model developed in this study has to analyze the long term effects of the lack of adequate spent-fuel disposition capability. Since long range planning is somewhat hypothetical, the solution contains hypothetical fractional elements. Nevertheless, since the model developed in this study is versatile and accurate, it can be applied successfully to actual planning.

Table 8.7. Net Profits of the Reprocessing Scenarios

Scenario	Reprocess Profit [10^6 \$]	Net profit [10^6 \$]				
		M = ∞	M = 3	M = 2.5	M = 2	M = 1.5
NR	0	-3189.4	-3243.	-3424.7	-4271.7	-6064.9
PS	1952.0	- 193.0	-195.2	-203.8	- 242.4	-1039.9
RR	2524.0	727.9	726.0	717.1	685.5	137.6
OR	3162.0	1778.3	1776.2	1767.6	1738.1	1383.0

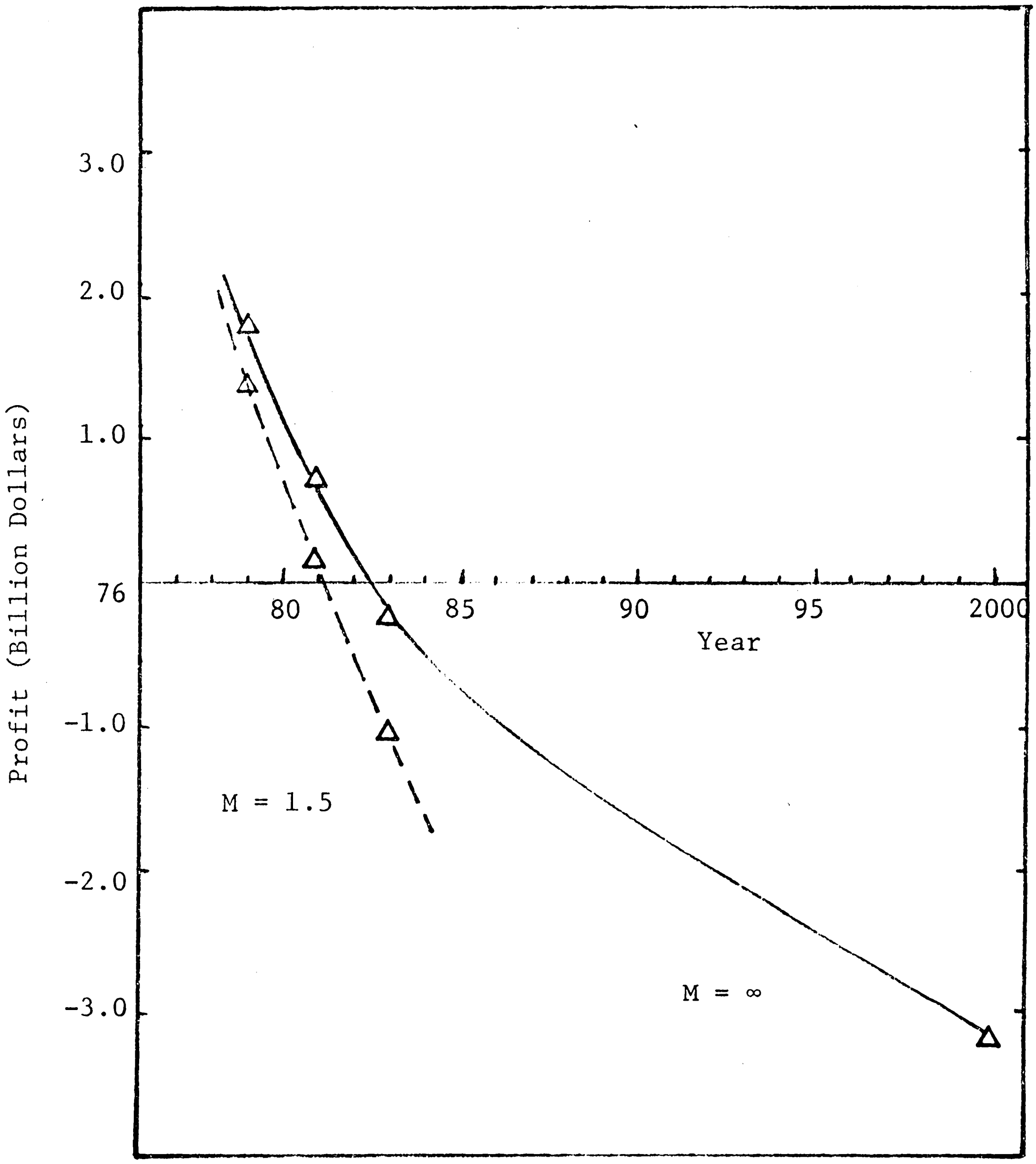


Figure 8.3. Net Profit of the Reprocessing Scenarios (1976 Dollars, 10% Discount Factor).

9. RECOMMENDATIONS FOR FURTHER WORK

In this study, a methodology which employs linear programming techniques has been developed to evaluate the cost effective strategies for the time and location dependent spent nuclear fuel storage capacity expansion. The computer program, which was implemented on the IBM System/370 Model, has allowed comparison of expenditures incurred by on-site and off-site spent-fuel storage capacity installations and spent-fuel operation requirements. Also potential revenues that can be realized by various alternate modes of recycling the fissile isotopes, uranium and plutonium, recovered from spent-fuel through reprocessing were estimated. In view of the importance of the conclusions of this study, several areas for additional work have been identified. This work can result in an improved treatment of the spent-fuel storage problem.

An important extension of this work can be an essentially straightforward expansion of the aggregate decision variables by considering explicit allocation of the on-site and off-site capacity and the associated spent-fuel transfer on a region-wise or reactor-site basis. Such extension of the model would permit selection of optimal off-site spent-fuel storage facilities with respect to the time dependent geographical configuration of the planned nuclear power plant installations.

An important application of the extended model might be its use in selection of the optimal sites for nuclear waste repositories. It has been reported recently that the Energy Research and Development

Administration has undertaken a study with the objective to evaluate about 36 potential sites for nuclear waste repositories.[68] While the purpose of that study is to determine relative merits of the sites on the basis of geological and environmental considerations, the extended model would also allow to select among the suitable sites those whose location would be optimal in terms of minimization of the transportation costs.

An additional application of the model developed in this study can be its use for determination of cost optimal spent-fuel storage capacity expansion strategies for other types of reactors such as natural-uranium-heavy-water-moderated reactors (CANDU), fast breeders, and HTGR's.

Another area of additional work related to this study can be stochastic treatment of certain parameters of the model. Among the parameters which are strongly influenced by probabilistic phenomena are the spent-fuel generation rate, reprocessing demand rate, and cost parameters.

Finally, in view of the interim spent-fuel storage becoming a viable fuel cycle option, development of nuclear fuel management models including spent-fuel storage and its function as an important fuel cycle alternative is recommended.

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Appendix 1.

The Genesis of Plutonium in LWR's

On the average each fissioning atom in LWR fuel emits about 2.1 neutrons, one of each is needed to sustain the fission reaction. When an atom of U238 absorbs a neutron with slower energy than necessary for its fission, it transforms to neptunium-239 and an electron. Neptunium-239 spontaneously transforms to plutonium 239, also by β decay, over relatively short time span.

U238	+ n	→	U239	+	γ	
U239		→	Np239	+	e^-	$t_{1/2}$ = 23.5 min
N239		→	Pu239	+	e^-	$t_{1/2}$ = 2.35 days

Occasionally an atom of U235 does not fission upon absorbing a neutron but instead it is transformed into heavier isotopes of uranium, thence into transuranium nuclides by a series of successive neutron absorptions and beta decay. The transformation relations are as follows:

U235	+ n	→	U236	+	γ	
U236	+ n	→	U237	+	γ	
U237		→	Np237	+	e^-	$t_{1/2}$ = 6.75 days
Np237	+ n	→	Np238	+	γ	
Np238		→	Pu238	+	e^-	$t_{1/2}$ = 2.12 days

Similarly, if some of the atoms of Pu239 will not undergo a fission, then they are transformed according to

$$Pu239 + n \rightarrow Pu240 + \gamma$$

Plutonium-240 is not fissile (it is fertile). Pu 240 due to high neutron cross-section readily absorbs neutrons to form the fissile isotope Pu-241 according to

$$Pu240 + n \rightarrow Pu241 + \gamma$$

Once again, however, some of the fissile Pu241 will absorb neutrons without fissioning

$$Pu241 + n \rightarrow Pu242 + \gamma$$

leading to the formation of non-fissile Pu242. The above transformations occuring in the LWR indicate that mainly neutron irradiation of U238 leads inevitably to production of plutonium isotopes. Pu239 and Pu241 are referred to as fissile plutonium.

Formation of Transplutonium Actinides:

Various transplutonium (actinide) radionuclides are also created in the LWR cores. The most important ones are described by following transformation relations

$$Pu241 \rightarrow Am241 + e^- \qquad t_{1/2} = 13.2 \text{ years}$$

$$Am241 + n \rightarrow Am242 + \gamma$$

$$Am242 \rightarrow Am242 + e^- \qquad t_{1/2} = 16.0 \text{ hours}$$

$$Pu242 + n \rightarrow Pu243 + \gamma$$

$$Pu243 \rightarrow Am243 + e^- \qquad t_{1/2} = 5.0 \text{ hours}$$

$$Am243 + n \rightarrow Cm244 + \gamma$$

These actinides are present in much higher quantities in the spent mixed-oxide fuels than in spent enriched-uranium fuels.

$$W_j = S_j \, r \, P_o, \tag{3}$$

where

P_o = quantity of fissile plutonium per unit quantity of spent-fuel.

Using the radioactive decay law, the loss of Pu-241 during period (j + 1) can be expressed as

$$\Delta L_j = F S_j \, \ell, \tag{4}$$

where

$\ell = e^{-0.0525}$

$F = r(1 - \ell) \, P_o$.

The cumulative loss of Pu-241, L_j, between periods j and m, for m > j, can be obtained by a summation of the yearly decayed quantities ΔL_j, for each period between j and m. The result is

$$L_j^m = S_j \, r \, P_o (1 - \ell) \sum_{n=0}^{m-j} \ell^n. \tag{5}$$

Using eq. (5), the total cumulative loss of fissile plutonium (Pu-239 + Pu-241) as a result of Pu-241 decay can be expressed as

$$L_K = F \sum_{j=1}^{K} S_j \sum_{m=0}^{K-j} \ell^m. \tag{6}$$

Equation (6) is associated with the spent-fuel discharged for periods 1 through K.

Appendix 2.

Derivation of the Uranium Enriched Product Value

An analysis of gaseous diffusion cascade[49,50] provides a value of enriched uranium feed, the cost of separative work and waste stream composition. The separative work required to produce P units of the enriched product is given by the expression

$$\Delta = PV(x_p) + WV(x_w) - FV(x_f) \qquad (1)$$

where

Δ = separative work in ideal cascade, Kg

P = amount of enriched product, Kg

W = amount of depleted uranium, Kg

F = amount of natural uranium, Kg

x_p = assay of U-235 in the enriched product, weight fraction

x_w = tails assay

x_f = U-235 assay of the feed uranium, weight fraction

V(x) is a mathematical function called "value function".[49] It is a dimensionless function of assay defined by the expression

$$V(x) = (2x - 1) \ \ell n \frac{x}{1-x} \qquad (2)$$

The equations for a total and fissile material balance, together with the equation for separative work, define the system. The material balance equations are

$$F = P + W \qquad (3)$$

and

$$Fx_f = Px_p + Wx_w \qquad (4)$$

The above relationships can be combined to give

$$\frac{F}{P} = \frac{x_p - x_w}{x_f - x_w} \qquad (5)$$

The equation representing the price of the enriched product can be derived from the separative work and material balance equations under the conditions, that the entire enrichment cost is charged to the product and that the tails assay will have no value. Then for the unit cost of the enriched product, D in \$ per Kg, the expression

$$D = C_s \frac{\Delta}{P} + C_f \frac{F}{P} \qquad (6)$$

reflects that the total unit cost of the enriched product equals the sum of the cost of separative work needed to produce one unit of the enriched product and the feed cost which is proportional to the relative feed material flow. The unit costs of separative work and feed material are C_s and C_f, respectively.

The equation for D can be solved by using the expressions for the separative work and the material balance. The result can be stated as

$$D = C_s[(2x_p - 1) \ln \frac{x_p}{1-x_p} - (2x_w - 1) \ln \frac{x_w}{1-x_w}$$

$$+ \frac{x_p-x_w}{x_f-x_w} ((2x - 1) \ln \frac{x_w}{1-x_w} - (2x_f - 1) \ln \frac{x_f}{1-x_f})] \qquad (7)$$

$$+ c_f \frac{x_p - x_w}{x_f - x_w} . \qquad (7)$$

Appendix 3.

Formulation of the Multistage Dynamic Optimization Problem

In order to be able to formulate mathematically a dynamic optimization problem, the following essential elements must be identified:

1. System equations which describe the process to be controlled.
2. The objective function which evaluates a particular decision policy.
3. The constraints which place restrictions on the system formulation.

The system equations (sometimes called transition relationships) are a set of relations between three types of variables: the stage variable, the state variables, and the decision variables. In fact, they represent interrelationships among the elements of the problem.

The stage variable determines the order in which the events and decisions take place in the system. This quantity varies monotonically over the horizon during which events occur and decisions are made. This variable in most situations takes on the discrete values $k = 0, 1, 2, \ldots, N$. The length of the horizon, N, (the upper limit on the stage variable, k,) can be infinite, but generally it is finite. The system status at any time is described by the state variables whose values at all $k = 0, 1, 2, \ldots, N$ are known and thus describe the evolution of the system. The choice of state variables to describe the system is not unique, and a suitable set must be chosen to describe adequately the nature and extent of the problem. There is also a requirement that these variables be non-redundant. If there are m state variables chosen, they can be written as an m-dimensional vector $\underline{u}$, called the state vector

$$\underline{u} = \begin{bmatrix} u_1 \\ u_2 \\ \cdot \\ \cdot \\ \cdot \\ u_m \end{bmatrix} .$$

Decision variables are those variables in the process which can be specified directly and which are to be determined by the optimization process. These variables affect the status of the system during its evolution. The fashion in which decision variables influence values of the state variables must be specified. In general, one can have n decision variables which can be arranged in a n-dimensional vector $\underline{x}$ (decision vector)

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_n \end{bmatrix} .$$

The transition relationships (system equations) describe how the state variables of stage k are related to the state variables at stage k-1 and the decision variables. These equations can be expressed as

$$u_i(k) = \phi_i\ (u_1(k - 1), u_2(k - 1), \ldots, u_m(k - 1); x_1(k), x_2(k), \ldots$$
$$x_n(k), k) \text{ for } i = 1, 2, \ldots, m \qquad (1)$$

or more compactly as

$$\underline{u}(k) = \underline{\Phi}[\underline{u}(k - 1), \underline{x}(k), k] \qquad (2)$$

where $\underline{\Phi}$ is an n-dimensional vector functional.

Common to all dynamic models is that current decisions affect state variable values in the present and subsequent periods. Consequently, the important economic trades-offs, if decisions have an economic impact, are not only between activities (decisions) with a single stage, but also between decisions in different stages. The objective function for the dynamic problem provides an evaluation of a given decision sequence $\underline{x}(1)$, $\underline{x}(2)$, ..., $\underline{x}(N)$. This function depends on each value of $\underline{x}(k)$ in the decision sequence, and also on the values of the state vectors $\underline{u}(0)$, $\underline{u}(1)$, ..., $\underline{u}(N)$. If the criterion is denoted by I, it can be written as

$$I = \sum_{k=0}^{N} R(\underline{u}(k), \underline{x}(k), k) \qquad (3)$$

The constraints place restrictions on the values that the state and decision variables can assume. Generally, the state vector $\underline{u}(k)$ at stage k is constrained to belong to a specified set U(k). This constraint can be expressed mathematically

$$\underline{u} \in U(k) \tag{4}$$

The decision vector applied at a state $\underline{u}$ and stage k can, in general, be constrained so belong to the set $X(\underline{u}, k)$, i.e.,

$$\underline{x} \in X(\underline{u}, k) \tag{5}$$

The problem then can be formulated as minimization (maximization) of objective function I

$$\text{Min } I = \sum_{k=0}^{N} R(\underline{u}, \underline{x}, k) \tag{6}$$

subject to

$$\underline{u} \in U(k)$$

$$\underline{x} \in X(\underline{u}, k) \tag{7}$$

A wide flexibility in the constraints can be provided.

Appendix 4.

Derivation of the Dynamic Programming Recursive Functional Form of the Objective Function

The derivation of the functional form of the objective function is shown here in the manner of Larson.[64]

Denoting $R(u_k, x_k, k)$ as cost (return) in time period k dependent on state u_k and decision variable x_k, the minimum cost that can be obtained by starting from a permissible state $u_k \varepsilon U$ at stage k can be written as

$$I(u_k, k) = \underset{x_j \varepsilon X}{\text{Min}} \sum_{j=k}^{N} R(u_j, x_j, j) \tag{1}$$

$$j = k, k+1, \ldots, N$$

Applying the decomposition principle, the summation can be split into two parts

$$I(u_k, k) = \underset{x_j \varepsilon X}{\text{Min}} [R(u_k, x_k, k) + \sum_{j=k+1}^{N} R(u_j, x_j, j)] \tag{2}$$

$$j = k, k+1, \ldots, N$$

Minimization can also be split into two parts: minimization over x_k and a minimization over decision variables $x_{k+1}, x_{k+2}, \ldots, x_N$. The result is

$$I(u_k, k) = \underset{x_k \varepsilon X}{\text{Min}} \; \underset{x_j \varepsilon X}{\text{Min}} [R(u_k, x_k, k) + \sum_{j=k+1}^{N} R(u_j, x_j, j)] \tag{3}$$

$$j = k+1, \ldots, N$$

It can be observed that the first term in the brackets depends only on x_k. Thus, minimization over x_j for $j > k$ has no effect on this term, i.e.,

$$\underset{x_k \in X}{\text{Min}} \; \underset{x_j \in X}{\text{Min}} \; [R(u_k, x_k, k)] = \underset{x_k \in X}{\text{Min}} \; [R(u_k, x_k, k)] \tag{4}$$

$$j = k+1, k+2, \ldots, N$$

The second term in (3) does not depend explicitly on x_k. But, x_k does determine the value of state variable u_{k+1} at stage k+1 through the state transition relationship

$$u_{k+1} = \Phi(u_k, x_k, k) \tag{5}$$

Using the minimum cost function (1) and relation (5) the following expression can be obtained

$$\underset{x_k \in X}{\text{Min}} \; \underset{x_j \in X}{\text{Min}} \; \sum_{j=k+1}^{N} R(u_j, x_j, j) = \underset{x_k \in X}{\text{Min}} \; I[\Phi(u_k, x_k, k), k+1]$$

$$j = k+1, \ldots, N \tag{6}$$

By introducing expressions (6) and (4) into eq. (1), a recursive functional equation can be obtained in the form

$$I(u_k, k) = \underset{x_k \in X}{\text{Min}} \; \{R(u_k, x_k, k) + I[\Phi(u_k, x_k, k), k+1]\} \tag{7}$$

The above equation is a mathematical statement of Belman's "principle of optimality." The equation states that a minimum cost for state u_k at stage k can be obtained by choosing the value of decision variable x_k which would minimize the sum of the cost at the current stage k and the minimum cost incurred from the end of stage k+1 to the end of the horizon.

The dynamic programming technique is generally implemented as a direct search procedure.[63] State vector $\underline{u}$ and decision vector $\underline{x}$ are quantized to discrete values and cost function $R(u_k, x_k)$ is evaluated at discrete values of decision variable x_k and the minimization of the recursive functional equation is performed by evaluation over all discrete values of state variable u_k. A global optimum is obtained within the accuracy of the quantization increments.

Appendix 5.

Linear Programming Theory

The purpose of LP is to determine the allocation of limited resources to competing activities in an optimal manner in order to achieve a certain production objective.

In general, the mathematical problem consists of a set of linear equations or inequalities relating decision variables-activities whose levels are sought such that some objective consisting of a linear combination of those activities is maximized or minimized. Mathematically, solving a linear program consists of the determination of variables $x_1, x_2, \ldots, x_N$ which minimize or maximize the objective function

$$I = \sum_{i=1}^{N} c_i x_i \tag{1}$$

which is subject to the following conditions:

$$\begin{aligned} a_{11} x_1 + a_{12} x_2 + \ldots + a_{1N} x_N \; [\leq_1 = {}_1\geq] \; b_1 \\ a_{21} x_1 + a_{22} x_2 + \ldots + a_{2N} x_N \; [\leq_1 = {}_1\geq] \; b_2 \\ a_{m1} x_1 + a_{m2} x_2 + \ldots + a_{mN} x_N \; [\leq_1 = {}_1\geq] \; b_m \end{aligned} \tag{2}$$

and also the requirement of non-negativity

$$x_i \geq 0 \qquad i = 1, 2, \ldots, N \tag{3}$$

where any of the signs $\leq$, $=$,$\geq$ holds for any constraint, where N is number of decision variables and m is number of constraints, and where c_i, b_i, and a_{ij} are known constants.

Any set of x_i which satisfies the constraints (2) is a solution. Any solution which also conforms to non-negativity requirements (3) is feasible solution, and any feasible solution which optimizes the objective function (1) is an optimal feasible solution.

In the system described by the objective function (1) and constraints (2) two basic properties of a linear model are implied. The first is multiplicavity, which requires that the measure of effectiveness and the resource usage must be directly proportional to each level of activity considered individually. The second property, additivity, stipulates that each resource usage can be expressed as a linear combination of the activity levels and also that the objective, a total measure of effectiveness, is the sum of effects resulting from each activity performed individually.

Another assumption, which on some occasions creates difficulties, is that the decision variables x_i can take on any values allowed by the constraints (2) and (3). Frequently, these variables represent items which have significance only as integers, but there is no guarantee that the solution will be all integers. Then, usually, a common procedure is to round-off each decision variable to the nearest integer. Generally, if the optimal solution is composed of activities each consisting of a large number of units, then the round-off procedure can be justified.

Finally, coefficients c_i, b_i, and a_{ij} are assumed to be known. Since LP is generally used for planning purposes, these coefficients are usually based on forecasts. Consequently, the degree of realism and difficulty of successful implementation of the LP solution is strongly related to the accuracy with which these constants are obtained. Procedures such as post optimality analysis and stochastic approaches are sometimes used when these coefficients are uncertain.[66]

Formulation of a LP model is only a part of the task. It must be solved. Some basic features of the LP solution will be discussed here. A thorough treatment of LP can be found in the literature.[66,67]

Small linear programming problems, with only two variables, can be solved geometrically. First, a feasibility region defined by the constraints and non-negativity requirements is located. The boundaries of that region, a convex polyhedron, are delimited by the straight lines defined by the constraints. Next, a family of indifference curves, equal profit curves, representing the objective function is constructed. Further to the right in the first quadrant the higher the curve lies the higher is the value of the objective function. The equal profit line furthest to the right having a point in common with the feasibility region identifies that point as the optimal solution to the problem. Most frequently this point is a corner point of the region of feasibility, and it is unique. However, it may happen that the profit line is identical with one of the boundaries of the feasibility region. In this case, instead of a solution, a set of solutions is obtained. Hence, it can be stated that there is an optimum solution, but the feasible solution is not unique. If a equal profit line furthest to the right of the first quadrant has a common point with the feasibility domain in infinity, such a solution is unbounded. Occurence of the unbounded solution is most likely due to an erroneous formulation of the problem. In practice, infinite profit and unlimited resources are not likely. In addition to the unbounded solution other exceptional cases may occur. For example, it may happen that there is not a set of decision variables which would satisfy all constraints. In this case the problem doe not have a feasible solution. Even though the above mentioned exceptional cases rarely occur in the real world, any solution technique should be able to identify them. These exceptional cases might occur, because the complexity of the problems to be solved by the LP technique may easily lead to mistakes during their formulation. There is also a special case where the problem has a single solution. This solution indicates that there is no freedom in the selection of values of the activities. This problem is better known as a set of simultaneous, linear equations.

The geometrical method is impractical for the solution of multi-dimensional problems. In 1947, George B. Dantzig developed the principal elements of linear programming, including the simplex algorithm, which enables solving a general linear programming problem in a finite number of iterations.[67]

The simplex method is an iterative process providing a solution to an LP problem after a finite number of stops. It disposes of a criterion by which one can make sure of the optimum solution, and it also identifies those neighboring solutions by which the objective function is increased. A great advantage of the simplex method is the use of a prior information in the search of extremum by inquiring into the logic of the matter. The simplex procedure starts from a known extreme point determined by the constraints. A system of linearly independent vectors, basis, can be assigned to this extreme point. By exchanging one and only one basis vector against a vector outside the basis, one proceeds along the edge to a neighboring solution, preferably to that one which adds most to the objective function. Proceeding in this manner iteratively, an optimum can be attained in a finite number of steps. If the extreme point is optimal, the simplex algorithm indicates this fact. Also if an "edge" is leading to infinity and the objective function along this edge increases too, then simplex algorithm indicates an unbounded solution.

Most LP computer codes use a revised form of the simplex method. The revised simplex method uses additional procedures with the finding of the outmost extreme point of the convex polyhedron formed by the restriction in the shortest possible way. One such code is the MPS III mathematical programming system for use with IBM computer System/370 Model 145 and above.[65]

The final step in the application of a LP model is the interpretation of the solution. In the application of LP to the spent fuel storage model a general plan for storage capacity expansion over many periods is sought. When the time element is involved, the

LP solution can identify the decision variables for a time period, but not the sequence of activities within the period. Therefore, a care must be exercised in the choice of time increment length.

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OPTIMIZATION OF TIME AND LOCATION DEPENDENT

SPENT NUCLEAR FUEL STORAGE CAPACITY

by

Victor Macek

(ABSTRACT)

In this study a linear spent fuel storage model is developed to identify cost-effective spent nuclear fuel storage strategies. The purpose of this model is to provide guidelines for the implementation of the optimal time-dependent spent fuel storage capacity expansion in view of the current economic and regulatory environment which has resulted in phase-out of the closed nuclear fuel cycle.

Management alternatives of the spent fuel storage backlog, which is created by mismatch between spent fuel generation rate and spent fuel disposition capability, are represented by aggregate decision variables which describe the time dependent on-reactor-site and off-site spent fuel storage capacity additions, and the amount of spent fuel transferred to off-site storage facilities. Principal constraints of the model assure determination of cost optimal spent fuel storage expansion strategies, while spent fuel storage requirements are met at all times.

A detailed physical and economic analysis of the essential components of the spent fuel storage problem, which precedes the model development, assures its realism.

The effects of technological limitations on the on-site spent fuel storage expansion and timing of reinitiation of the spent fuel reprocessing on optimal spent fuel storage capacity expansion are investigated.

The principal results of this study indicate that

a) expansion of storage capacity beyond that of currently planned facilities is necessary, and

b) economics of the post-reactor fuel cycle is extremely sensitive to the timing of reinitiation of spent fuel reprocessing.

Postponement of reprocessing beyond mid-1982 may result in net negative economic liability of the back end of the nuclear fuel cycle.