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Budget Estimates for Replacement of Plant and Facility Equipment at the NBS Campuses

Phillip T. Chen
Robert E. Chapman

NBS-Gaithersburg, Maryland

NBS-Boulder, Colorado

Building Economics and Regulatory Technology Division
Center for Building Technology
National Engineering Laboratory
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PREFACE

This study was conducted by the Building Economics and Regulatory Technology Division, Center for Building Technology, National Engineering Laboratory, for the Plant Divisions at Gaithersburg and Boulder, to demonstrate how economic principles and rehabilitation technology can be applied to the planned replacement of the aging and obsolete plant equipment at the National Bureau of Standards. James G. Gross, Carl O. Muehlhause, James H. Pielert, Harold E. Marshall, William G. Hall, David A. Didion, Thomas K. Faison, and Frank H. Lerchen provided general reviews of this paper. Preston E. McNall, Tamami Kusuda, Paul R. Achenbach, James Y. Kao, James H. Hill, Robert R. Jones, Lawrence S. Galowin, Robert G. Mathey and Felix Y. Yokel provided technical consultation. Bruce E. Thompson provided computer services, Mary M. Chaney, Catherine Nowstrup and Charity Starr provided production services, and the numerous persons in the Plant Division at Gaithersburg and Boulder provided data, guidance and review.

The authors wish to express their appreciation to the above persons, without whose help this study could not have been completed.

EXECUTIVE SUMMARY

The replacement of aging plant and facility equipment is a major concern of all Federally-owned and operated installations. Past efforts at equipment replacement, however, have often underutilized information on the service life distribution of a particular component/system. More specifically, equipment was usually maintained until it either failed or reached some average age at which time total replacement was initiated.

This study develops a framework, based on service life distributions fitted to data from a published survey, for dealing with the "replacement problem." Service life distributions are used to develop replacement schedules for approximately 50 major plant and facility equipment items at the National Bureau of Standards (NBS) Gaithersburg and Boulder sites.[1] Two sets of costs associated with these replacement schedules are estimated. The first approach produces an estimate of the expected replacement cost for each item over the ten-year planning horizon. This approach makes use of a manual procedure referred to as the cost factor model. The second approach produces both annual and total cost estimates over the ten-year planning horizon. This approach makes use of a computerized procedure referred to as the probabilistic cost model. Estimates from this model are intended for use in budgeting for replacements over the planning horizon.

The results of this study indicate that the total annual estimates for 10 years, in terms of first quarter 1980 dollars, for equipment replacement at the NBS Gaithersburg and Boulder sites are approximately:

FISCAL YEAR		TOTAL
1982		1,702,000
1983		1,615,000
1984		1,667,000
1985		1,647,000
1986		1,575,000
1987		1,511,000
1988		1,462,000
1989		1,353,000
1990		1,318,000
1991		1,304,000
	TOTAL	15,154,000

[1] The Gaithersburg, Maryland site was built between 1963 and 1968 on 589 acres of land and includes 27 buildings; the 1980 replacement value of the entire facility is $325 million. The Boulder, Colorado site was built between 1955 and 1957 on 205 acres of land and includes nine buildings; the 1980 replacement value of the entire facility is $40 million.

Based on the results of this study, three areas of additional work are identified.

First, prior to the actual replacement of any equipment, the appropriate engineering studies should be performed. Furthermore, life-cycle cost techniques should be used to ensure that the most cost-effective items (which are technically feasible in the engineering sense) are selected for replacement.

Second, a data bank which will permit the validation and modification of equipment service lives actually experienced at the NBS campuses should be developed and maintained. In addition to providing information on equipment services lives, such a data bank would facilitate the process (either manually or via computer calculations) of identifying and pursuing more cost-effective levels of equipment maintenance.

Third, this study should be updated at least every five years to support the NBS budget planning process.

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SI Conversion Units

The following list of selected conversion factors for the most frequently used quantities in building design and construction may be used.

QUANTITY	INTERNATIONAL (SI) UNIT	U.S. CUSTOMARY UNIT	APPROXIMATE CONVERSION	
LENGTH	meter (m)	foot (ft)	1 m	= 3.2808 ft
	millimeter (mm)	inch (in)	1 mm	= 0.0394 in
AREA	square meter (m^2)	square yard (yd^2)	1 m^2	= 1.1960 yd^2
		square foot (ft^2)	1 m^2	= 10.764 ft^2
	square millimeter (mm^2)	square inch (in^2)	1 mm^2	= 1.5500 x 10^{-3} in^2
VOLUME	cubic meter (m^3)	cubic yard (yd^3)	1 m^3	= 1.3080 yd^3
		cubic foot (ft^3)	1 m^3	= 35.315 ft^3
	cubic millimeter (mm^3)	cubic inch (in^3)	1 mm^3	= 61.024 x 10^{-6} in^3
CAPACITY	liter (L)	gallon (gal)	1 L	= 0.2642 gal
	milliliter (mL)	fluid ounce (fl oz)	1 mL	= 0.0338 fl oz
VELOCITY, SPEED	meter per second (m/s)	foot per second (ft/s or f.p.s.)	1 m/s	= 3.2808 ft/s
	kilometer per hour (km/h)	mile per hour (mile/h or m.p.h.)	1 km/h	= 0.6214 mile/h
ACCELERATION	meter per second squared (m/s^2)	foot per second squared (ft/s^2)	1 m/s^2	= 3.2808 ft/s^2
MASS	metric ton (t) [1000 kg]	short ton [2000 lb]	1 t	= 1.1023 ton
	kilogram (kg)	pound (lb)	1 kg	= 2.2046 lb
	gram (g)	ounce (oz)	1 g	= 0.0353 oz
DENSITY	metric ton per cubic meter (t/m^3)	ton per cubic yard (ton/yd^3)	1 t/m^3	= 0.8428 ton/yd^3
	kilogram per cubic meter (kg/m^3)	pound per cubic foot (lb/ft^3)	1 kg/m^3	= 0.0624 lb/ft^3
FORCE	kilonewton (kN)	ton-force (tonf)	1 kN	= 0.1124 tonf
		kip [1000 lbf]	1 kN	= 0.2248 kip
	newton (N)	pound-force (lbf)	1 N	= 0.2248 lbf
MOMENT OF FORCE, TORQUE	kilonewton meter (kN•m)	ton-force foot (tonf•ft)	1 kN•m	= 0.3688 tonf•ft
	newton meter (N•m)	pound-force inch (lbf•in)	1 N•m	= 8.8508 lbf•in
PRESSURE, STRESS	megapascal (MPa)	ton-force per square inch ($tonf/in^2$)	1 MPa	= 0.0725 $tonf/in^2$
		ton-force per square foot ($tonf/ft^2$)	1 MPa	= 10.443 $tonf/ft^2$
	kilopascal (kPa)	pound-force per square inch (lbf/in^2)	1 kPa	= 0.1450 lbf/in^2
		pound-force per square foot (lbf/ft^2)	1 kPa	= 20.885 lbf/ft^2
WORK, ENERGY, QUANTITY OF HEAT	megajoule (MJ)	kilowatthour (kWh)	1 MJ	= 0.2778 kWh
	kilojoule (kJ)	British thermal unit (Btu)	1 kJ	= 0.9478 Btu
	joule (J)	foot pound-force (ft•lbf)	1 J	= 0.7376 ft•lbf
POWER, HEAT FLOW RATE	kilowatt (kW)	horsepower (hp)	1 kW	= 1.3410 hp
	watt (W)	British thermal unit per hour (Btu/h)	1 W	= 3.4121 Btu/h
		foot pound-force per second (ft•lbf/s)	1 W	= 0.7376 ft•lbf/s
COEFFICIENT OF HEAT TRANSFER [U-value]	watt per square meter kelvin (W/m^2•K) [= (W/m^2•°C)]	Btu per square foot hour degree Fahrenheit (Btu/ft^2•h•°F)	1 W/m^2•K	= 0.1761 Btu/ft^2•h•°F
THERMAL CONDUCTIVITY [k-value]	watt per meter kelvin (W/m•K) [= (W/m•°C)]	Btu per square foot degree Fahrenheit (Btu/ft^2•°F)	1 W/m•K	= 0.5778 Btu/ft^2•°F

NOTES: (1) The above conversion factors are shown to three or four places of decimals.

(2) Unprefixed SI units are underlined. (The kilogram, although prefixed, is an SI base unit.)

REFERENCES: NBS Guidelines for the Use of the Metric System, LC1056, Revised August 1977;

The Metric System of Measurement, Federal Register Notice of October 26, 1977, LC 1078, Revised November 1977;

NBS Special Publication 330, "The International System of Units (SI)," 1977 Edition;

NBS Technical Note 938, "Recommended Practice for the Use of Metric (SI) Units in Building Design and Construction," Revised edition June 1977;

ASTM Standard E621-78, "Standard Practice for the Use of Metric (SI) Units in Building Design and Construction," (based on NBS TN 938), March 1978;

ANSI Z210.1-1976, "American National Standard for Metric Practice;" also issued as ASTM E380-76$^{\epsilon}$, or IEEE Std.268-1976.

ABSTRACT

The replacement of aging plant and facility equipment is a major concern of all Federally-owned and operated installations. Past efforts at equipment replacement have often underutilized information on the service life distribution of a particular component/system. More specifically, equipment was usually maintained until it either failed or reached some average age at which time total replacement was initiated.

This study develops a framework, based on service life distributions fitted to data from a published survey, for dealing with the "replacement problem." Service life distribution are used to develop replacement schedules for approximately 50 major plant andd facility equipment items at the National Bureau of Standards (NBS) Gaithersburg and Boulder sites. The costs associated with these replacement schedules are estimated on an annual basis over a ten-year planning horizon using a probabilistic cost model. Estimates from this model are intended for use in budgeting for replacements over the planning horizon. The results of this study indicate that approximately \$15 million (all estimates are in first quarter of 1980 dollars) will be needed to meet expected replacements during fiscal years 1982 through 1991 at the NBS Gaithersburg and Boulder sites.

Key Words: Building maintenance; cost engineering; economic analysis; rehabilitation cost.

1. INTRODUCTION

The replacement of aging plant and facility equipment is a major concern of all Federally-owned and operated installations. Past efforts at equipment replacement however, have often underutilized information on the service life distribution of a particular component/system. More specifically, equipment was usually maintained until it either failed or reached some average age at which time total replacement was initiated. The current maintenance program of the physical plant at the National Bureau of Standards (NBS) follows this approach in that it focuses on the repair of major plant and facility equipment of system components. Consequently, as the system components in the physical plant age and their remaining useful lives shorten, replacement rather than repair becomes highly probable.

The replacement of obsolete equipment represents a unique opportunity to apply techniques from engineering, economics and operations research to the "replacement problem." More specifically, data on service life distributions for approximately 50 major plant and facility equipment items are used to develop replacement schedules and the annual costs required to support these schedules for the NBS Gaithersburg and Boulder sites. Furthermore, Executive Order 12003, dated July 20, 1977, states that by 1985 all existing Federally-owned buildings shall have the average annual energy use per gross square foot of floor area reduced by 20 percent compared to the energy consumption in 1975. Consequently, energy conservation should play a major role in the selection of replacement equipment at the NBS.

The NBS is widely recognized as a leader in the development and application of engineering economics techniques for making cost-effective decisions regarding alternative building components/systems. Among these techniques are parametric cost estimation, computer simulation and life-cycle costing. Using these techniques as firm technical underpinnings, it is possible to develop a planned budgeting strategy for the replacement of aging and obsolete plant and facility equipment.

1.1 BACKGROUND

On September 5, 1978, the Plant Division of the Center for Facilities Management (CFM) sent an Interdivision Work Order (IWO-351-5028) to the Building Economics and Regulatory Technology Division (BERT), Center for Building Technology (CBT), for conducting a preliminary replacement study. Pursuant to this request, a report entitled Preliminary Study of Planned Replacement of Plant and Facility Equipment at the NBS Gaithersburg Site[1] was prepared and transmitted to both Plant Divisions in November 1978.

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[1] Phillip T. Chen, Preliminary Study of Planned Replacement of Plant and Facility Equipment at the NBS Gaithersburg Site, National Bureau of Standards, NBSIR 78-1567, November 1978.

As a result of the above study, the Gaithersburg Plant Division requested, on February 13, 1979, that the Building Economics and Regulatory Technology Division conduct a plant equipment replacement study for both the Gaithersburg and Boulder sites. Due to insufficient funding, however, the effects of energy conservation and program changes could not be included within the framework of this replacement study.

As part of the above study, a Letter Report was transmitted to both Plant Divisions on May 14, 1979. This report contained preliminary cost estimates for facility modernization activities at both sites for fiscal years 1981, 1982, and 1983.

At various times during this study, progress briefings have been made to Dr. Thomas A. Dillon, NBS Deputy Director, and to the personnel from the Office of the Director of Administrative and Information Systems (Units 320 and 351), and Office of the Associate Director for Programs, Budget and Finance (Units 111, 112, and 114).

1.2 PURPOSE

The goal of this study is to estimate the annual plant equipment replacement cost. This study is needed because much of the NBS plant and facility equipment service life has already exceeded its expected useful life or will exceed it in the next decade. These annual cost estimates cover both the NBS Gaithersburg and Boulder sites for a ten-year period beginning in FY82.[1] The annual cost estimates are derived by first distributing and then summing up the individual engineering cost estimates over the ten-year period.

This study does not include the annual replacement cost of plant equipment items due to technical obsolescence. Technical obsolescence is most likely caused by: (1) a change in NBS research needs; (2) a change in national policy, such as barrier free design; and (3) the need to conserve energy due to rapidly rising energy costs and Presidential directives.

1.3 SCOPE

The approach for this study includes the collection and selection of basic information on equipment replacement, the selection and application of evaluation methods, and the presentation and assessment of the results of this evaluation.

1.3.1 Information Sources[2]

The information presented in this study was derived from five basic sources:

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[1] The rationale behind the selection of a ten-year planning period is given in section 2.2.

[2] See appendix A for a complete listing of information sources.

(a) Interviews with the engineering and operating personnel of Plant Divisions at Gaithersburg and Boulder;

(b) Inspections of physical plants at Gaithersburg and Boulder, including representative equipment items;

(c) NBS budget for facility maintenance, modifications, and improvements;

(d) Equipment service life data from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE),[1] equipment manufacturers, local contractors and NBS operations and maintenance records; and

(e) Cost data from past experience of the Plant Divisions, local area governments, manufacturers, contractors and the 1979 edition of the R. S. Means Mechanical and Electrical Cost Data[2] guide.

1.3.2 Evaluation Methods

The methods for analyzing and synthesizing the replacement information consist of:

(a) Performing qualitative analyses on equipment component history to determine which plant equipment items are good candidates for replacement.

(b) Establishing service lives for the candidate replacements;

(c) Developing engineering cost estimates for the replacement of plant equipment items; and

(d) Performing an economic synthesis to define annual cost estimates based on the most likely plant equipment replacements which will occur over the ten-year period beginning in FY82.

1.3.3 Evaluation Results

The results of this study consist of:

(a) Annual replacement costs of plant equipment due to physical obsolescence at both the NBS Gaithersburg and Boulder sites for ten years starting from FY82;

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[1] Mustafa T. Akalin, "Equipment Life and Maintenance Cost Survey," ASHRAE Journal, October 1978.

[2] Mechanical and Electrical Cost Data: 1979, Second Edition, Robert Snow Means Company, Inc., Kingston, Massachusetts, 1979.

(b) Recommendations of engineering studies[1] capable of identifying plant replacements required due to technical obsolescence; and

(c) Guidelines for using economic concepts to ensure that plant equipment replacements at the NBS sites are carried out in the most cost-effective manner.[2]

1.4 ORGANIZATION

The report includes two technical chapters and three appendices. In particular, the report is organized along these lines.

Section 2.1 includes a discussion of engineering considerations associated with each plant replacement item, background information on the distribution of the service life for each item and itemized engineering cost estimates. Section 2.2 focuses on the economic evaluation methods used in this study as well as methods recommended for use in evaluating equipment replacements due to technical obsolescence. Section 3 includes the summary and recommendations for further work.

Three technical appendices are also included. They are concerned with: (A) a complete listing of information sources; (B) engineering studies related to energy conservation and technical obsolescence; and (C) economic principles and applications suitable for replacement studies.

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[1] See appendix B for the listing and discussion of engineering studies. The costs of replacing equipment which are technologically obsolete are not included in this study.

[2] See appendix C for a listing and discussion of economic principles and applications.

2. DESCRIPTION OF PLANNED REPLACEMENT STUDY

2.1 ENGINEERING CONSIDERATIONS

Based on the information sources listed in section 1.3.1, the following topics are included as engineering considerations for this study: site descriptions; plant equipment service life; engineering cost estimates; and summary tables and discussion.

2.1.1 Site Descriptions

(a) Gaithersburg site - The average age of the buildings is 15 years. Since most of the buildings were designed by one architectural-engineering firm, which had worked closely with GSA and NBS personnel in an earlier planning phase, the building systems such as roofs, HVAC, plumbing and electrical distribution, are similar in design, workmanship, maintainability and durability. Furthermore, a good maintenance program (both regular and preventive) has been in continuous operation since building occupancy. Therefore, of the approximately 90 groups of equipment in Gaithersburg, only 29 groups are identified as needing replacement. (The selection of the 29 groups was based on consultation with the Plant Division.) These groups are listed in table 2.1.

(b) Boulder site - The average age of buildings at Boulder is 25 years. Many of the HVAC systems are either window units or small systems added to the buildings after occupancy. Most of the buildings are dissimilar in design. However, because of a good maintenance and operation program, the building systems and components are still in use despite their old age. The situation in Boulder is further complicated by the requirement to share occupancy with other Federal agencies which are not a part of the NBS and do not have similar facility requirements. In this study 18 groups, listed in table 2.2, are defined as in need of replacement over the ten-year period beginning in FY82. (The selection of the 18 groups was based on consultation with the Plant Division.)

2.1.2 Plant Equipment Service Life

Service life is defined as the number of years before the total replacement of the system/component is likely to be initiated. Previous studies[1] have concluded that equipment service life is generally influenced by the following five factors:

(a) Replacement with an identical item becomes less costly than continued maintenance and repair;

(b) Replacement with an identical item becomes necessary to ensure reliability and safety;

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[1]Mustafa T. Akalin, "Equipment Life and Maintenance Cost Survey," ASHRAE Journal, October 1978.

(c) Advanced technology suggests replacement due to lower operating costs for new equipment;

(d) Changing requirements necessitate replacement to meet new needs not within the capabilities of existing equipment; and

(e) Human desires dictate replacement for non-economic reasons.

Since this study only deals with physical obsolescence, only factors (a) and (b) are considered. Although factors (c), (d) and (e) are beyond the scope of this report, a methodology is outlined which will facilitate the assessment of equipment replacements falling into factors (c) and (d).

Generally, the expected service life of a particular piece of plant equipment is obtained through consideration of the following:

(a) The service life estimates published by or obtained from the manufacturer or respective trade association;

(b) The effect that a particular arrangement of the total system is likely to have on the service life of an individual piece of equipment; and

(c) The effect that an operation and maintenance procedure is likely to have on the equipment service life, i.e., the historical engineering performance of the existing plant.

For this study, the service lives of plant equipment items were derived from the following sources: ASHRAE, manufacturers, contractors, local governmental records and NBS records. Engineering judgment was used when service life data were not available from any of the above sources.

In order to facilitate the distribution of engineering cost estimates over several consecutive years, the service lives of plant equipment items are expressed in three statistical terms. These terms are the Mode, the 25th percentile, and the 75th percentile. In the context of this study:

(a) The "Mode" is defined as the year in which the greatest number of identical items (i.e., of the same kind of plant equipment) will require replacement.

(b) The "25th percentile" is defined as the year by which 25 percent of the same kind of plant equipment items will have required replacement.

(c) The "75th percentile" is defined as the year by which 75 percent of the same kind of plant equipment items will have required replacement.

The three statistical terms associated with service life are listed in tables 2.1 and 2.2. To illustrate the relationship of these three statistical terms to service life, the following data from table 2.2 are presented:

		SERVICE LIFE IN YEARS			
GROUP	EQUIPMENT	MODE	25%	75%	QUANTITY
10	Fan Coil Unit	20	15	22	180

The service life of the fan coil units is expressed using three terms:

(a) The 20th year is the single year during which a replacement of a fan coil unit is most likely to occur.

(b) At the end of 15 years, 25 percent of all fan coil units (45 units) will have been replaced.

(c) At the end of 22 years, 75 percent of all fan coil units (135 units) will have been replaced.

2.1.3 Engineering Cost Estimates

Engineering economic principles usually distinguish among three types of cost estimates. These three types of estimates, in increasing order of accuracy, are:

(a) Order of Magnitude;

(b) Ball Park; and

(c) Detailed.

Each term is defined here in terms of the "possible" spread about the expected bid price for the contract. An order of magnitude estimate is expected to be only accurate to a spread of ± 100 percent of the bid price, a ball park estimate is expected to be within ± 30 percent, and a detailed estimate within ± 5 percent. In general, order of magnitude estimates are used only in the conceptual phase. Planning activities are usually conducted using ball park figures. Detailed estimates are prepared at the same time as the engineering deign parameters are established.

The engineering cost estimate for a plant equipment item is defined as the estimated total cost, in 1980 dollars (first quarter), to replace an old piece of equipment with an identical or similar piece. The estimated total cost includes engineering design cost, disconnecting cost, the removal cost of the item, reconnecting cost of the new item, and all related overhead costs and/or profit if it is done by an outside contractor. Salvage value is not included since it is dependent on the physical condition of the equipment item and, as such, cannot be estimated at this time. In this study, it is assumed that the engineering design will be done at the time of replacement need so that all estimated costs are of "ball park" accuracy. The engineering cost estimates, expressed in dollars of the first quarter of 1980, are divided into three types:

(a) "Most likely" engineering cost estimates are the realistic cost estimates for the replacement which will most likely be needed in the ten-year period beginning in FY82. These estimates are based on the probabilistic cost model[1] described in section 2.2.

(b) "CFME" (Cost Factor Model Estimates) are engineering cost estimates based on a parametric cost estimation procedure. They cover equipment replacements which may be needed for the ten years beginning in FY82.

(c) "Total Replacement" estimates are the one-time costs of replacing the equipment items in a group or a component of a group. It is simply equal to the quantity of the equipment item times the unit cost of the item.

All three types of cost information are included in the cost engineering estimates presented in tables 2.1 and 2.2.

The CFME figures may be numerically derived from the total replacement cost figure through use of a cost factor model. This model separates, or factors, the current age of the plant equipment and the length of the planning horizon, in this case ten years. A deflator, actually the mode of the service life distribution, is then used to measure the expected replacement potential of the system/component. In order to apply the cost factor model, each item was broken up into a homogeneous group. For example, as shown in equipment group 3 for the Gaithersburg site, 144 bearings were replaced five years ago and the remaining 800 are 15 years old. If we denote the total replacement estimate as TR, the equipment age as EA, the planning horizon as PH, and the 75th percentile as P(75), the CFME figures are defined as:

$$\mathrm{CFME} = (\mathrm{TR})[(\mathrm{EA}/\mathrm{Mode})-((\mathrm{P}(75)-\mathrm{EA})/\mathrm{Mode})+(\mathrm{PH}/\mathrm{Mode})] \qquad (1)$$

$$\text{where } (\mathrm{EA}/\mathrm{Mode}) \leq 1$$

In equation (1) the term TR(EA/Mode) represents the expected total cost of equipment replacement to date. The term (EA/Mode) is a probability factor for total replacement of equipment to date. The term TR[(P(75)-EA)/Mode] represents the total cost avoided during the planning horizon. The term ((P(75)-EA)/Mode) is a deflator representing a probability factor for that portion of the existing equipment not replaced and expected to last throughout the planning horizon. Similarly the term TR(PH/Mode) represents cost of equipment replacement within the planning horizon.

It is important to point out that the mode is used as the denominator in all three terms in equation (1). The mode is only one of three measures of central tendency, however. The other two are the mean (the average service

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[1]The computerized probabilistic cost model is also used to produce other baseline cost estimates. These estimates, which are discussed in section 2.2, include: "theoretical replacement cost;" "no historic replacement cost;" and "most likely replace costs with a one, two or three year delay."

Table 2.1 Engineering Considerations: Gaithersburg Site

No.	Equipment Group Name	Equipment Group Quantity	Component Quantity	Component Name	Age in Years	Service Life in Years: Mode	25%	75%	Estimates in 1980 Dollars X 1000, 10 Year Total: Most Likely	CFME	Total Replacement	Comments
1	Air Compressor	2	2	Water Jacket	17	18	10	20	10	17	12	For the whole site
			4	Piston & Cylinder	17	18	15	20	12	17	12	
			2	After Cooler	17	16	10	20	14	29	20	
			9		15	20	15	25	24	27	36	For individual building
2	Air Conditioner	9			17	13	8	15	6	17	9	
	Console	3			7	13	8	15	3	2	3	New replacement
3	Air Handler Unit	236	210	Coil & Support	15	20	15	30	574	630	1260	
			26	Coil & Support	5	20	15	30	46	0	155	New replacement
			800	Bearing	15	18	15	20	250	267	240	
			144	Bearing	5	18	15	20	2	0	43	New replacement
			472	Motor & Starter	15	20	15	30	129	142	283	
			472	Fan	15	25	20	40	339	0	1086	
			944	Pneumatic Control	15	20	15	20	48	47	47	
4	Air Receiver	30			15	20	15	25	21	23	30	
5	Air Separator Tank	7			15	18	15	25	4	6	7	
6	Air Washer	2			15	30	20	30	11	7	20	
7	Boiler	1			3	25	20	30	2	0	10	Oil fired
		1			11	30	25	35	3	0	10	Gas fired
8	Condensate Pump	36			15	15	10	25	18	36	36	
		4			3	15	10	25	2	0	4	New replacement
9	Cooling Tower	1	4	Fan Stack	17	16	15	20	62	86	60	
			4	Gear Box, Shaft & Motor	17	18	15	20	103	133	100	
			4	Butterfly Valve	17	18	15	20	17	21	16	
			1 Lot	Wood Deck & Fill	8	10	8	10	142	160	100	
			1	Sprinkler System	14	15	10	20	17	30	25	Fire protection
10	Electrical System	1 Lot	100	Primary and Secondary Switch	17	30	25	38	308	200	1000	
			1	Primary Switch Gear at sub-station	17	--	--	--			4500	
11	Exhaust, Fume	138	368	Fume Hood[a]								
			110	Duct, Corrosive Exhaust	15	20	15	20	395	385	385	30% of total
			258	Duct, Non-Corrosive	15	40	30	50	146	0	903	
			60	Fan, Corrosive	15	15	10	20	41	80	60	
			50	Fan, Corrosive	5	15	10	20	32	0	50	New replacement
			258	Fan, Non-Corrosive	15	25	20	35	101	52	258	
12	Exhaust, Laboratory	138	138	Duct	15	40	30	50	78	0	483	
			138	Fan	15	25	20	35	54	28	138	

Notes:

[a] Normally, fume hoods are project related items, therefore they are not included in the estimate.

Table 2.1 Engineering Considerations: Gaithersburg Site (Continued)

No.	Equipment Group Name	Equipment Group Quantity	Component Quantity	Component Name	Age in Years	Service Life in Years: Mode	25%	75%	Estimates in 1980 Dollars X 1000, 10 Year Total: Most Likely	CFME	Total Replacement	Comments
13	Expansion Tank	23			15	20	15	20	24	23	23	
		5			5	20	15	20	2	0	5	New replacemnt
14	Heat Exchanger Chilled Water	18			15	20	15	20	41	45	90	
15	Heat Exchanger Hot Water	50			15	25	20	30	43	30	75	
16	Insulation Mechanical Service	1 Lot	80,000 ft.	Interior Piping	15	20	20	40	193	0	560	
			1 Lot	Steam Manholes	15	15	10	20	41	80	60	
			1 Lot	Interior, Duct Work	15	20	20	30	308	250	500	
17	Land Work	1 Lot										Annual cost is $10K
18	Perimeter Fence	1			15	--	--	--	66	60	60	
19	Piping	1 Lot	11,200 ft.	55°F Chilled Water	15	15	10	20	181	299	224	
20	Pumps	201			12	20	15	24	315	322	402	
		24			7	20	15	24	18	0	48	New replacement
21	Refrigeration Unit		3	Gear Box	17	20	10	25	97	143	150	
			1	Gear Box	5	20	15	25	18	0	50	New replacement
			4	Rotor, Motor	17	20	10	20	69	96	80	
			4	Motor Insulation	5	20	10	20	23	0	40	New replacement
			12	Motor Starter & Breaker	17	15	10	30	85	168	210	
			4	Insulation	17	20	20	30	62	70	100	
			4	Booster Pump	17	20	15	25	41	57	60	
			4	Valve	17	25	20	30	9	9	16	
22	Roof	983,000 S. F.			15	20	15	25	1668	1845	2460	
23	Road, etc.		824,000 S. F.	Road Resurfacing	15	15	12	20	1362	2480	1860	
			12,000 S. F.	Parking Lot Resurfacing	15	15	12	20	878	1600	1200	
			83,000 L. F.	Curb replacement	15	40	30	50	134	0	830	
24	Safety		1	CO_2 System	15	20	15	23	13	50	20	For Fire Protection Building 236
			1 Lot	Heat Detector	15	--	--	--	5	5	5	200 units for 10 years
			1 Lot	Smoke Detector	15	--	--	--	13	12	12	50 units for 10 years
25	Steam Generator	4	4	Back	17	20	15	20	246	288	240	
			4	Tube	17	20	15	20	33	38	32	
			12	Valve	17	18	15	20	37	48	36	
			1 Lot	Insulation	17	22	20	30	45	58	75	
			1 Lot	Boiler Auxiliaries	17	20	15	25	51	71	75	

Table 2.1 Engineering Considerations: Gaithersburg Site (Continued)

No.	Equipment Group Name	Quantity	Component Quantity	Component Name	Age in Years	Service Life in Years: Mode	25%	75%	Estimates in 1980 Dollars X 1000, 10 Year Total: Most Likely	CFME	Total Replacement	Comments
26	Underground Piping	1 Lot	16,600 L. F.	Chilled Water Supply & Return	15	20	15	20	699	0	4316	
			13,900 L. F.	Condensate in RICWIL	15	30	25	35	272	128	765	
			13,900 L. F.	Steam in RICHWIL	15	35	25	45	449	0	2085	
			14,600 L. F.	Natural Gas	15	40	30	50	95	0	584	
			26,000 L. F.	Water	15	50	30	60	150	0	1300	
27	Valve	1 Lot	19	Back Flow Preventor	15	20	15	25	26	29	38	
			700	Building & System	15	25	20	20	237	168	420	
28	Vacuum Pump	25			15	20	15	25	34	38	50	
		5			5	20	15	25	3	0	10	New Replacement
29	Wall Expansion Joint				15							One time cost is $50K

Table 2.2 Engineering Considerations: Boulder Site

No.	Equipment Group Name	Quantity	Component Quantity	Component Name	Age in Years	Service Life in Years: Mode	Service Life in Years: 25%	Service Life in Years: 75%	Estimates in 1980 Dollars X 1000, 10 Year Total: Most Likely	Estimates in 1980 Dollars X 1000, 10 Year Total: CFME	Total Replacement	Comments
	Air Compressor	22			21	20	15	25	53	86	66	
	Air Conditioner, Window Unit	300			10	10	5	10	212	300	150	
3	Air Washer	3			20	30	20	30	35	30	45	
4	Boiler	12			25	30	20	35	78	120	144	
5	Domestic Hot Water Heater	10			15	20	15	27	12	13	20	
			12	Primary Switch	27	40	35	50	52	63	180	
			72	Secondary Switch	25	40	35	50	105	90	360	
6	Electrical System	1 Lot	2000 L.F.	Underground wiring	20	--	--	--		50	50	One time need is $50K
			4	Emergency Generator	15	20	15	25	30	30	40	
			28	Transformer	27	30	20	40	111	202	252	
			150	Battery	20	12	10	15	19	34	15	
			20	Fume Hood a/	--							
			20	Fume Hood Duct Work and Fan, Corrosive	10	20	15	20	105	50	100	
7	Exhaust	195							221	333	500	
			125	Laboratory Exhaust Duct Work and Fan	25	30	20	40				
			30	Other	25	35	25	45	21	26	60	
8	Expansion Tank and Air Receiver	20			20	20	15	25	32	50	60	
			7	Hoist & Crane	20	25	20	30	20	22	28	
9	Hoist Elevator and Crane		2	Dock Levelator	15	25	20	30	2	2	4	
			2	Elevator	20	30	20	40	15	13	40	
		1 Lot	26	Overhead Door	20	25	20	30	36	42	52	
			75	Air Handler Unit	20	25	20	30	394	450	563	
			15	Package Unit	15	20	15	25	55	56	75	
10	HVAC System	1 Lot	180	Fan Coil Unit	12	20	16	22	72	54	90	
			64	Refrigeration Unit	15	20	15	20	531	480	480	
			11	Cooling Tower	22	20	15	27	69	138	110	
			1000 L.F.	Pipe	20	20	15	25	7	10	8	
			60	Valve, 3" and above	25	25	20	30	23	36	30	
			400	Valve, below 3"	22	25	20	30	37	38	40	
11	Piping System	1 Lot	400	Steam Trap	25	15	10	20	39	80	40	
			5000 L.F.	Insulation	18	20	20	40	9	8	25	
			52	Expansion Joint	25	20	15	25	24	39	26	
			16	Acid Neutralizing Tank	5	15	10	20	3	0	5	
			5000 L.F.	Underground Piping, Water	25	30	25	35	70	83	100	

NOTES:

a/ Since fume hoods are project related items, they are not included in the estimates.

Table 2.2 Engineering Considerations: Boulder Site (cont.)

No.	Equipment Group Name	Equipment Group Quantity	Component Quantity	Component Name	Age in Years	Service Life in Years: Mode	25%	75%	Estimates in 1980 Dollars X 1000, 10 Year Total: Most Likely	CFME	Total Replacement	Comments
12	Pump	95	75	Circulating	20	20	13	24	90	147	113	
			20	Condensate	22	15	10	25	52	117	80	
13	Land Work				--	--	--	--				Annual cost is $10K
14	Lighting	1 Lot	66	Street and Parking Lot	27	30	20	40	14	26	33	
			5000	Interior Fixture	15	25	20	30	290	200	500	
15	Road	1 Lot	285000 S.F.	Roadway Resurfacing	15	15	12	20	356	532	399	
			30000 S.F.	Parking Lot Resurfacing	15	15	12	20	37	56	42	
			3000 L.F.	Concrete Curb	27	40	30	50	13	16	45	
16	Roof	300000 S.F.			15	20	15	25	667	675	900	
17	Safety	1 Lot	20	Fire Detector	5	15	10	20	6	0	10	
			60	Pull Station	15	20	15	25	9	9	12	
			100	Fire Bell	15	20	15	25	14	15	20	
			200	Emergency Light Battery Power	10	12	10	20	44	50	60	
18	Wall Surface Exterior	1 Lot	4000 L.F.	Concrete Sun Shade	27	35	30	40	46	55	80	
			50000 S.F.	Concrete Surface	25	40	30	50	70	63	250	

life) and the median (the year by which 50 percent of the same kind of plant equipment items will have required replacement). Due to the belief that maintenance management policies tend to respond to changes in equipment replacements (in particular increases), the mode was selected for use rather than the mean or the median. More succinctly, as equipment ages the rate at which it must be replaced increases over some time period. Maintenance policies respond by anticipating a higher replacement schedule in the following year(s). Consequently, by the time the mode is reached, it is quite likely that the decision to initiate total replacement of all equipment beyond some certain average will have been made.

Most likely estimates are the results of a probabilistic cost model based on computerized calculations using the service life distribution for each item. The probabilistic cost model is discussed in section 2.2.

The results of the calculations made with equation (1) and the most likely estimates are listed in tables 2.1 and 2.2.

2.1.4 Summary of Engineering Considerations

Table 2.1, Engineering Considerations: Gaithersburg Site, and table 2.2, Engineering Considerations: Boulder Site, are included as summaries of the information presented in sections 2.1.2 through 2.1.3.

The information contained in these two tables is used in section 2.2 for computing the most likely estimates. The CFME estimates shown in the tables are "ball park" figures obtained with the use of equation (1) in section 2.1.3. These estimates are useful for the preliminary selection and evaluation of replacement candidates before computer applications. The ten-year most likely estimates are the results of a series of computer applications and are discussed in section 2.2.

The engineering aspects associated with tables 2.1 and 2.2 are discussed in section 2.1.5.

2.1.5 Discussion

Based on tables 2.1 and 2.2, the following observations of the engineering considerations for Gaithersburg and Boulder can be made.

A. Gaithersburg Site

The following equipment groups appear to require substantial replacement within ten years.

(1) Group 1, Air Compressor - The water jacket, piston, cylinder and after cooler, components for the two compressors supplying air to the whole site, are expected to be replaced within ten years.

(2) Group 3, Air Handler Unit - The 800 bearings listed are expected to be replaced within ten years. The 144 bearings which were replaced five years ago will need minimum replacement in the next ten years.

(3) Group 8, Condensate Pump - 21 condensate pumps are expected to be replaced within ten years.

(4) Group 9, Cooling Tower - The five components listed are expected to be replaced within ten years. The most likely estimates of the component replacement costs for ten years are $341,000, as compared to a total replacement cost estimate of $700,000.

(5) Group 10, Electrical System - In order to reduce the likelihood of electrical power interruption due to potential equipment failure and voltage drop, some parts of the primary switch gear at the substation will have to be stocked since the manufacturer, Federal Pacific, no longer will make and supply these parts after January 1980. The above parts, sufficient for the next five years, will be purchased by the Plant Division. A study is being conducted by the Plant Division to replace the whole primary switch gear system at the substation by 1985. The preliminary cost estimate for this complete replacement is $4,500,000 and is not included in the annual replacement estimate.

(6) Group 14, Heat Exchangers, Chilled Water - Most of the heat exchangers for the 55°F chilled water may have to be replaced due to contamination by corrosion. The 55°F chilled water is supplied for laboratory equipment cooling.

(7) Group 19, Piping, 55°F Chilled Water - This steel piping is corroded internally. It should be replaced by copper tubing in order to provide an improved quality of cooling water for laboratory equipment.

(8) Group 21, Refrigeration Unit - The most likely estimate for component replacement is $404,000 for the next ten years. This replacement is needed to assure the efficient operation of the four refrigeration units, the complete replacement estimate of which would be $3,000,000.

(9) Group 22, Roof - Most of the roof areas are expected to be replaced within ten years.

(10) Group 24, Safety - The CO_2 system for fire protection in Building 236 is expected to be replaced. 200 heat detectors and 50 smoke detectors may be found to be defective within ten years and, therefore, will require replacement.

(11) Group 25, Steam Generator - The backs, tubes and valves for the four steam generators are expected to be replaced within ten

years. These generators are the source for building heat and processing steam. In addition to the replacement of backs, tubes and valves, thermal insulation and boiler auxiliaries (water softener, etc.) are the remaining replacement needs within ten years. The most likely replacement estimate is $42,000 for the five components, while the total replacement cost of these four generators is estimated to be $1,200,000.

(12) Group 27, Valve - Replacement is needed for 12 backflow preventors to assure the supply of clean and safe domestic water in the buildings. Some of the 700 valves, 3 inches and above in size, may have to be replaced also.

The replacements of the following equipment groups are also essential for the operation of buildings:

(13) Group 26, Underground Piping - Some portions of the condensate return piping inside of the Ricwil[1] are expected to be replaced within ten years due to corrosion within the pipe and outside of the Ricwil.

(14) Items within the remaining equipment groups analyzed in Table 2.1 of the study but not specifically discussed above.

The following items, although not included in this study, are good candidates for evaluation five years hence because replacement for these items may be needed ten years from now.

(15) Elements of building envelope, such as walls, construction joints, facia, mullions, etc. Roofing, although being an element of the building envelope, has been included as equipment Group 22.

(16) Elevators, hoists, cranes, dock elevators and dumbwaiters are also good candidates for evaluation five years from now.

(17) Laboratory furniture and laboratory services should also be evaluated five years from now.

B. Boulder Site

The following equipment groups appear to require substantial replacement.

(1) Group 1, Air Compressor - All 22 air compressors are expected to be replaced within ten years.

(2) Group 2, Air Conditioner, Window Unit - All 300 units are expected to be replaced at least once within ten years.

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[1] Trade name of the underground piping system in use at the Gaithersburg site. Mention of the trade name is not intended as an endorsement of the product.

(3) Group 4, Boiler - 6 of the 12 boilers listed are expected to be replaced.

(4) Group 6, Electrical System - 3 emergency generators are expected to be replaced. The 150 batteries are also expected to be replaced. Some of the 28 transformers are expected to be replaced within ten years.

(5) Group 9, Hoist, Elevator and Crane - Some portions of the hoists, cranes and overhead doors are expected to be replaced within ten years.

(6) Group 10, HVAC System - Some of the package units, refrigeration units and cooling towers are expected to be replaced within ten years.

(7) Group 11, Piping System - Some of the valves, steam traps and expansion joints are expected to be replaced. The 500 feet of underground piping will also need replacement due to corrosion.

(8) Group 12, Pump - Some of the circulating and condensate pumps are expected to be replaced within ten years.

(9) Group 14, Lighting - Some of the 5000 interior lighting fixtures will be replaced due to the fact that the existing fixtures are no longer suitable for laboratory work.

(10) Group 15, Roof - The roofing of some areas is expected to be replaced. In particular, new edge treatment is required for the area adjacent to the parapets, expansion joints and facia.

(11) Group 17, Safety - Some of the batteries for emergency lights are expected to be replaced.

(12) All remaining groups listed in table 2.2, but not discussed above, are also essential for the effective operation of buildings and sites.

(13) Within five years, it is suggested that all laboratory furniture and laboratory services be evaluated for possible need of replacement.

2.2 ECONOMIC CONSIDERATIONS

The purpose of this section is to discuss how the engineering principles presented earlier can be synthesized into a set of annual cost estimates. These cost estimates, based on the probabilistic cost model, are intended for use as budgetary planning figures over the ten-year period beginning in FY82. The selection of a ten-year planning period for this study was intended to satisfy three criteria. First, due to the current age of the plant equipment at both the Gaithersburg and Boulder sites, it is likely that many, if not a majority, of the major pieces of equipment will have to be replaced by the end of the planning period. Second, a ten-year period is short enough to ensure that most of the engineering considerations are based on sound technical underpinnings. In addition, a relatively short period serves to keep uncertainty within manageable bounds. Third, a ten-year planning period represents two five-year planning periods back-to-back. As such, the estimates can be viewed as being valid primarily only over the first five-year period and then be "refitted" to a second five-year period for future reference.

2.2.1 Cost Considerations

Two types of cost considerations are important in the preparation of budgetary planning figures. These two types are:

(a) Initial cost considerations; and

(b) Life-cycle cost considerations.

Initial costs may be defined in terms of direct costs and indirect costs. Those costs that a contractor incurs if he undertakes a specific job (i.e., labor costs including: fringe benefits, social security, workmen's compensation, unemployment insurance, bonding, risk acceptance, and the cost to the contractor for building materials and construction equipment) are called <u>direct costs</u>. Those costs that the contractor incurs regardless of whether he undertakes a specific job or not (e.g., rental payments for clerical and secretarial labor and payments for management) are called <u>indirect costs</u>. The ratio of indirect costs to direct costs is usually referred to as the mark-up factor. A mark-up factor is important because it can be varied somewhat depending on the contracting mode. For example, the replacement of a severely deteriorated piece of equipment might be accomplished at a lower price thorugh in-house replacement because NBS, rather than a private contractor, is assuming the risk for a cost overrun. Generally speaking, due to the greater risk of a cost overrun, contractor mark-ups are significantly higher in renovation activities than in new construction activities. Since all estimates in this study are assumed to be "ball park" figures, however, no assumptions about a specific contracting mode will be made. The decision as to the contracting mode is best left to the time when the relevant engineering parameters are defined.

Life-cycle cost techniques differ from initial cost considerations in that they explicitly take into account all costs (i.e., owning, operating and maintaining) which occur over the period under study. Thus, if a particular component were installed in the cooling tower and due to a lack of long-tem durability had to be replaced every five years, then the value of the cash flows resulting from periodic replacement must be estimated. These cash flows should in principle include any escalation in construction costs as well as incorporate a measure of the time value of money. Using the initial cost figure rather than the life-cycle cost figure would <u>understate</u> the true cost of using the cooling tower component mentioned earlier. To pursue this topic a bit further, suppose an alternative component for the cooling tower has a higher initial cost but is expected to last 15 years.

Thus if we compared the two alternatives over a given time horizon, say 15 years, then it is possible that the more expensive component from an initial cost viewpoint is less costly from a life-cycle cost viewpoint due to its greater long-term durability. Only with life-cycle costing will the "true" costs of ownership over the time horizon be represented.

It is important to point out, however, that the degree of sophistication gained through the life-cycle cost approach requires that detailed engineering specifications be available. Ideally, these specifications would be based on the results of special engineering studies. Since this study assumes that an item is replaced with a like item, no changes in operational characteristics are permitted. Consequently, no alternatives are considered. Under this rather confining assumption, life-cycle costing provides little new information. The emphasis of this study will thus be on the use of initial cost figures to facilitate the preparation of a baseline budget over the ten-year planning period. Guidelines for applying life-cycle cost techniques are provided in appendix C. This approach was taken to ensure that, as replacement became necessary and additional engineering information on the system became available, it would be possible to use the funds allocated for replacement in the most cost-effective manner.

2.2.2 Data Base Development

The development of a data base is the key step which enables the engineering considerations discussed earlier to be translated into a set of expected annual cost figures. The actual development of a data base makes use of statistical techniques as well as techniques from operations research. In tables 2.1 and 2.2 three types of service life figures are given. These figures provide the years corresponding to the 25th percentile, the mode, and the 75th percentile. The mode is stressed, rather than the mean or the median, because it represents the year where replacement is most likely to occur. Furthermore, under certain reasonable assumptions, the use of the three measures discussed above permits additional information about the overall service life distribution to be obtained. In particular, if the service life distribution is assumed to be triangular (see figure 2.1), these three points permit the entire service life distribution to be approximated. It is important to point out that authorities in the area of simulation modeling have advocated the use of either a Beta or triangular distribution if the data available on the process being modeled are sketchy.[1] The decision to use a triangular, rather than a Beta, distribution in this study was based primarily on computational ease. Another important factor which favored the triangular, distribution over other potential service life distributions (e.g., the normal or the uniform) was that it allowed skewness to be incorporated into the modeling process. For example, the mean (average) service life of a particular component may be 20 years but the mode, the year where the largest number of components are replaced, may be 23 years. Thus the use of the mean exclusively (as is commonly done) would tend to force the budgeted replacement funds to become "out-of-phase" with the required replacement funds.

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[1] Phillip F. Ostwald, <u>Cost Estimating for Engineering and Management</u>, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974.

The annual cost estimates are based on the probabilistic cost model. The key pieces of information used to exercise the probabilistic cost model are presented in tables 2.3 and 2.4. Table 2.3 summarizes data used in preparing the annual estimates for the Gaithersburg site. Table 2.4 is concerned with the Boulder site. The cost model is referred to as probabilistic because component replacements are scheduled based on a service life (probability) distribution. Individual replacement costs, however, are assumed to be constant rather than distributed over some range specified by a probability distribution. In addition to the total replacement cost for each piece of equipment/component, seven additional pieces of information were used in exercising the probabilistic cost model. These data are:

(a) the item count;
(b) the age of the equipment;
(c) the low point of the service life distribution;
(d) the 25th percentile;
(e) the mode;
(f) the 75th percentile; and
(g) the high point of the service life distributio.

The item count is used to determine the unit replacement cost and the expected number of item replacements that will be required in a given year based on the respective probability distribution. The unit replacement cost is then used to determine the total annual expected cost due to replacements. The age of the equipment is used to ensure that each category of plant equipment examined is as homogeneous as possible. Given the approach taken in this study, this requirement is particularly important. The last five pieces of information define the service life (probability) distribution.

Data for each item on the 25th percentile, the mode, and the 75th percentile, were used to fit the two end points of the triangular distribution. See figure 2.1 for an example of a fitted triangular distribution using the information on the fan coil units presented earlier. A computerized procedure was then used to estimate the number of theoretically ideal replacements which should have occurred prior to the present time period (i.e., the age of the equipment). This figure was then compared to the historical replacement cost schedule to determine what proportion of the theoretically ideal replacements were actually installed.[1] The remainder thus represents items which should have been replaced, but for various reasons were not. The proportion which remains is defined as the probability of "theoretical" replacement. Suppose this figure was calculated as 20 percent, that the age of the equipment is 17 years, and that the maximum life of the equipment is 36 years. Since all of the equipment is currently in use, the 20 percent of the population corresponding to "theoretical" replacements are still candidates for potential

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[1] Replacement cost schedules for each site were reconstructed from the records of the respective Plant Division. Adjustments into first quarter 1980 dollars were made using the Engineering New Record Building Construction Cost Index.

replacements in the future. Therefore, in order to avoid an underestimate of the potential replacements, the 20 percent of the population which are "theoretical" replacements are uniformly distributed over the period from the present to the maximum life of the equipment. In this case, the probability of a replacement in a given year (between years 17 and 36) would experience a net increase of one percent. Alternative methods could be used to distribute the "theoretical" replacements; however, the assumption that they are uniformly distributed across the remainder of the service life distribution was appealing both from a conceptual and a computational viewpoint. The computerized procedure then calculates the expected number of replacements in each year and the cost of replacement. It then sums the costs across all items for each year. The figure which results is the expected annual budget required to cover all items expected to require replacement in that year.

2.2.3 Annual Cost Figures

The annual cost figures plotted in figures 2.2 and 2.3 are the result of the application of the probabilistic cost model to the data bases for Gaithersburg and Boulder, respectively. The vertical axis of each figure shows the expected annual replacement cost in 1980 dollars. The horizontal axis of each figure enumerates each of the fiscal years for which the site was in use through FY1991. Each expected annual replacement cost produced by the probabilistic cost model is designated by a circle, hexagon, or a triangle.

Three sets of annual cost estimates for each site are provided to show the potential effects of alternative historical equipment replacement scenarios. The first set of estimates, those designated by a circle, are based on the theoretically ideal replacement scenario. In this scenario equipment is replaced based solely on the service life distribution defined in tables 2.3 and 2.4. The second set of estimates, those designated by a hexagon, are based on the historical replacement cost schedule for each site. In this scenario only a proportion of the theoretically ideal replacements are installed so that an increment of "theoretical" replacements is built up. This increment is then distributed uniformly over the remaining service life of the item.[1] The third set of estimates, those designated by a triangle, are based on the assumption that no expenditures for equipment replacement took place until FY82. This scenario is included as an upper bound estimate for comparison against any actual or planned replacement program. It also serves

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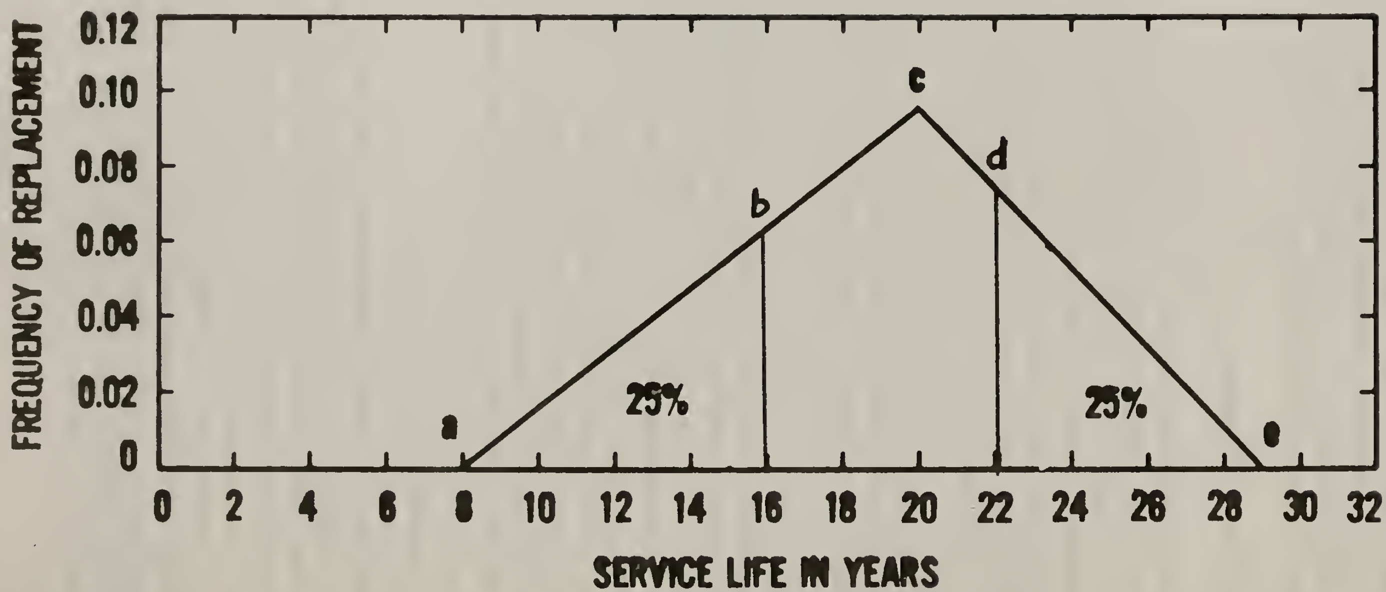
[1] The proportion of ideal replacements actually installed for each year may vary. For example, at the Gaithersburg site the ratio of actual expenditures to the theoretically ideal replacement funds tends to decline up through FY81, whereas for Boulder it is a constant 20 percent through FY81. For any given year the proportion of a particular item replaced is equal to the proportion of theoretically ideal replacement funds required that were actually spent. This approach was used because it was not possible to get item-by-item breakdowns from the historical records. The estimates of actual replacement costs up through FY81 each site plotted in figures 2.2 and 2.3 were provided by the respective Plant Division.

FIGURE 2.1 EXAMPLE OF A FITTED TRIANGULAR DISTRIBUTION USING DATA ON THE 25TH PERCENTILE, THE MODE, AND THE 75TH PERCENTILE



a - minimum service life
b - 25th percentile point
c - mode
d - 75th percentile point
e - maximum service life

TABLE 2.3 EQUIPMENT SERVICE LIFE DISTRIBUTIONS: GAITHERSBURG SITE

GROUP NO.	EQUIPMENT/ COMPONENT	QUANTITY	AGE IN YEARS	CRITICAL POINTS IN SERVICE LIFE DISTRIBUTION LOW	25%	MODE	75%	HIGH
1	Water Jacket	2	17	0	10	18	20	27
	Piston & Cylinder	4	17	9	15	18	20	25
	After Cooler	2	17	0	10	16	20	29
		9	15	4	15	20	25	36
2	Air Conditioner	9	17	0	8	13	15	21
	Air Conditioner	3	7	0	8	13	15	21
3	Coil & Support	210	15	0	15	20	30	48
	Coil & Support	26	5	0	15	20	30	48
	Bearing	800	15	9	15	18	20	25
	Bearing	144	5	9	15	18	20	25
	Motor & Starter	472	15	0	15	20	30	48
	Fan	472	15	0	20	25	40	65
	Pneumatic Cont	944	15	8	15	20	20	24
4	Air Receiver	30	15	4	15	20	25	36
5	Air Separator Tank	7	15	5	15	18	25	38
6	Air Washer	2	15	6	20	30	30	38
7	Boiler	1	3	8	20	25	30	42
	Boiler	1	11	13	25	30	35	47
8	Condensate Pump	36	15	0	10	15	25	40
	Condensate Pump	4	3	0	10	15	25	40
9	Fan Stack	4	17	10	15	16	20	27
	Gear Box, Shaft and Motor	4	17	9	15	18	20	25
	Butterfly Valve	4	17	9	15	18	20	25
	Wood Deck & Fill	1	8	5	8	10	10	12
	Sprinkler System	1	14	0	10	15	20	30
10	Replacement Parts for Primary and Secondary Switch	100	17	10	25	30	38	55
	Primary Switch Gear to Pepco	1	17	--	--	--	--	--
11	Fume Hood	368	15	--	--	--	--	--
	Duct	110	15	8	15	20	20	24
	Duct	258	15	5	30	40	50	75
	Fan	60	15	0	10	15	20	30
	Fan	50	5	0	10	15	20	30
	Fan	258	15	3	20	25	35	54
12	Duct	138	15	5	30	40	50	75
	Fan	138	15	3	20	25	35	54
13	Expansion Tank	23	15	8	15	20	20	24
	Expansion Tank	5	5	8	15	20	20	24
14	Heat Exchanger Chilled Water	18	15	0	15	20	30	48
15	Heat Exchanger Hot Water	50	15	8	20	25	30	42

TABLE 2.3 EQUIPMENT SERVICE LIFE DISTRIBUTIONS: GAITHERSBURG SITE (cont.)

GROUP NO.	EQUIPMENT/ COMPONENT	QUANTITY	AGE IN YEARS	CRITICAL POINTS IN SERVICE LIFE DISTRIBUTION LOW	25%	MODE	75%	HIGH
16	Interior Piping	80,000	15	5	20	20	40	67
	Steam Manholes	1	15	0	10	15	20	30
	All Other	1	15	12	20	20	30	44
17	Landscaping	1	15	--	--	--	--	--
18	Perimeter Fence	1	--	--	--	--	--	--
19	55°F CH H_2O	11,200	15	0	10	15	20	30
20	Pumps	201	15	4	15	20	24	35
	Pumps	24	7	4	15	20	24	35
21	Gear Box	3	17	0	10	20	25	35
	Gear Box	1	5	4	15	20	25	36
	Rotor	4	17	0	10	20	20	26
	Motor Insulation	4	5	0	10	20	20	26
	Motor Starter & Breaker	12	17	0	10	15	30	50
	Insulation	4	17	12	20	20	30	44
	Booster Pump	4	17	4	15	20	25	36
	Valve	4	17	8	20	25	30	42
22	Roof	983,000	15	4	15	20	25	36
23	Road Resurfacing	824,000	15	3	12	15	20	30
	Parking Resurfacing	12,000	15	3	12	15	20	30
	Curb Replacement	83,000	15	5	30	40	50	75
24	CO_2 System	1	15	4	15	20	25	36
	Heat Detector	1	15	--	--	--	--	--
	Smoke Detector	1	15	--	--	--	--	--
25	Back	4	17	8	15	20	20	24
	Tube	4	17	8	15	20	20	24
	Valve	12	17	9	15	18	20	25
	Insulation	1	17	10	20	22	30	43
	Boiler Auxiliary	1	17	4	15	20	25	36
26	Chilled Water Supply & Return	16,600	15	5	30	40	50	75
	Condensate in Ricwil	13,900	15	13	25	30	35	47
	Steam in Ricwil	13,900	15	1	25	35	45	69
	Natural Gas	14,600	15	5	30	40	50	75
	Water	26,000	15	0	30	50	60	90
27	Back Flow Preventor	19	15	4	15	20	25	36
	Bldg. & Sys.	700	15	8	20	25	30	42
28	Vacuum Pump	25	15	4	15	20	25	36
	Vacuum Pump	5	5	4	15	20	25	36

TABLE 2.4 EQUIPMENT SERVICE LIFE DISTRIBUTIONS: BOULDER SITE

GROUP NO.	EQUIPMENT/ COMPONENT	QUANTITY	AGE IN YEARS	CRITICAL POINTS IN SERVICE LIFE DISTRIBUTION LOW	25%	MODE	75%	HIGH
1	Air Compressor	22	21	4	15	20	25	36
2	Air Conditioner Window Unit	300	10	0	5	10	10	13
3	Air Washer	3	20	6	20	30	30	38
4	Boiler	12	25	0	20	30	35	52
5	Domestic Hot Water Heater	10	15	1	15	20	27	42
6	Primary Switch	12	27	19	35	40	50	69
	Secondary Switch	72	25	19	35	40	50	69
	Underground Wiring	2,000	20	--	--	--	--	--
	Emergency Generator	4	15	4	15	20	25	36
	Transformer	28	27	0	20	30	40	60
	Battery	150	20	5	10	12	15	21
7	Fume Hood	20	--	--	--	--	--	--
	Fume Hood Duct Work and Fan	20	10	8	15	20	20	24
	Laboratory Exhaust Duct Work and Fan	125	25	0	20	30	40	60
	Other	30	25	1	25	35	45	69
8	Expansion Tank and Air Receiver	20	20	4	15	20	25	36
9	Hoist and Crane	7	20	8	20	25	30	42
	Dock Elevator	2	15	8	20	25	30	42
	Elevator	2	20	0	20	30	40	60
	Overhead Crane	26	20	8	20	25	30	42
10	Air Handler Unit	75	20	8	20	25	30	42
	Package Unit	15	15	4	15	20	25	36
	Fan Coil Unit	180	12	8	16	20	22	29
	Refrigerator Unit	64	15	8	15	20	20	24
	Cooling Tower	11	22	1	15	20	27	42
11	Pipe	1,000	20	4	15	20	25	36
	Valve 3" and Larger	60	25	8	20	25	30	42
	Valve 3" and Smaller	400	22	8	20	25	30	42
	Steam Trap	400	25	0	10	15	20	30
	Insulation	5,000	18	5	20	20	40	67
	Expansion Joint	52	25	4	15	20	25	35
	Acid Neutralizing Tank	16	5	0	10	15	20	30
	Underground Piping	5,000	25	13	25	30	35	47
12	Circulating Pump	75	20	0	13	20	24	36
	Condensate Pump	20	22	0	10	15	25	40
13	Landscaping	--	--	--	--	--	--	--
14	Street & Parking Lot	66	15	0	20	30	40	60
	Interior Fixture	5,000	15	8	20	25	30	42
15	Roadway Resurfacing	285,000	15	3	12	15	20	30
	Parking Lot Resurfacing	30,000	15	3	12	15	20	30
	Concrete Curb		27	5	30	40	50	75
16	Roof	300,000	15	4	15	20	25	36
17	Fire Detector	20	5	0	10	15	20	30
	Pull Station	60	15	4	15	20	25	36
	Fire Bell	100	15	4	15	20	25	36
	Emergency Light, Battery Powered	200	10	0	10	12	20	33
18	Conc. Sun Shade	4,000	27	18	30	35	40	52
	[illegible]. Surface	50,000	25	5	30	40	50	75

as a baseline against which the implications of funding delays can be compared (see the sensitivity analyses presented in section 2.2.4). Note that, in each case, the annual cost estimates begin with the first year of building occupancy for each site. (Thus in figure 2.2 the annual estimates begin with FY65 and in figure 2.3 they begin with FY55.) As in all other parts of this study, estimates are presented in terms of first quarter 1980 dollars.

It is important to point out that a portion of the "theoretical" replacements may fail in use and hence require immediate replacement at some time during the ten-year planning period. Since the per unit replacement cost figures used to establish the total replacement cost estimates presented in tables 2.1 and 2.2 are based on ideal replacement conditions, it is quite likely that the costs of immediate replacement may significantly exceed those of the best-case replacement conditions. In order to accommodate such situations, the replacement costs for items expected to experience a failure during the ten-year planning period were factored up by an optimistic estimate of the extra costs associated with an immediate replacement. More succinctly, the added costs associated with equipment failures in the historical replacement cost schedules represent no more than a 10 percent mark-up for any item; the estimates associated with the no previous replacement cost schedules include no more than a 15 percent mark-up for any item. No mark-up is applied to any item in either of the theoretical replacement cost schedules.

Since the estimates shown in figures 2.2 and 2.3 are reasonably smooth, a budget curve has been approximated by connecting each set of points. Due to the fact that appropriations are now usually distributed over more than one year, it is believed that this approach will facilitate long-range planning. The expected annual replacement costs for Gaithersburg are summarized in table 2.5. The expected annual replacement costs for Boulder are summarized in table 2.6. It is important to point out that, since all cost figures presented in this report are in terms of first quarter 1980 dollars, in future years it will be necessary to escalate these costs to reflect the true cost of item replacement at that time.

2.2.4 Assessing the Sensitivity of the Budget Estimates to Changes in the Timing of Funds for Equipment Replacement

The purpose of this section is to provide background information on how a change in the timing of funds for equipment replacement will affect the expected annual replacement cost figures between FY82 and FY91. These sensitivity analyses are designed to answer a series of "what if" questions related to potential delays in the allocation of funds needed to undertake the replacement of aging equipment.

The estimates presented in this section are the result of the application of the probabilistic cost model to the data bases for Gaithersburg and Boulder, respectively. The annual estimates for each site are shown in figures 2.4 and 2.5.[1] The estimated costs for Gaithersburg are shown in

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[1] The cost estimates presented in figures 2.4 and 2.5 do not include any additional operating or maintenance costs due to replacement delays.

Fig. 2.2 Alternative replacement cost schedules for Gaithersburg site

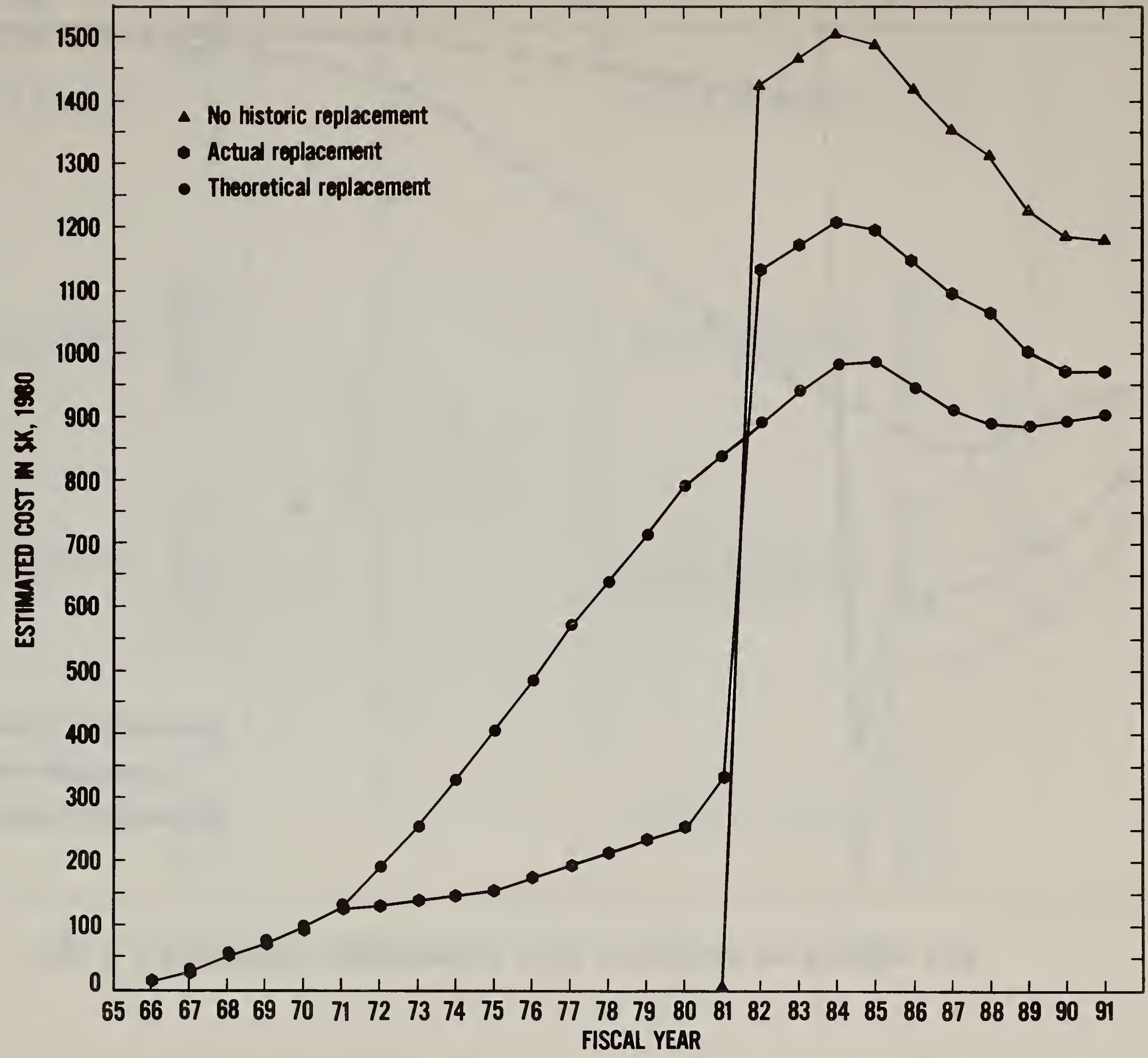

Fig. 2.3 Alternative replacement cost schedules for Boulder site

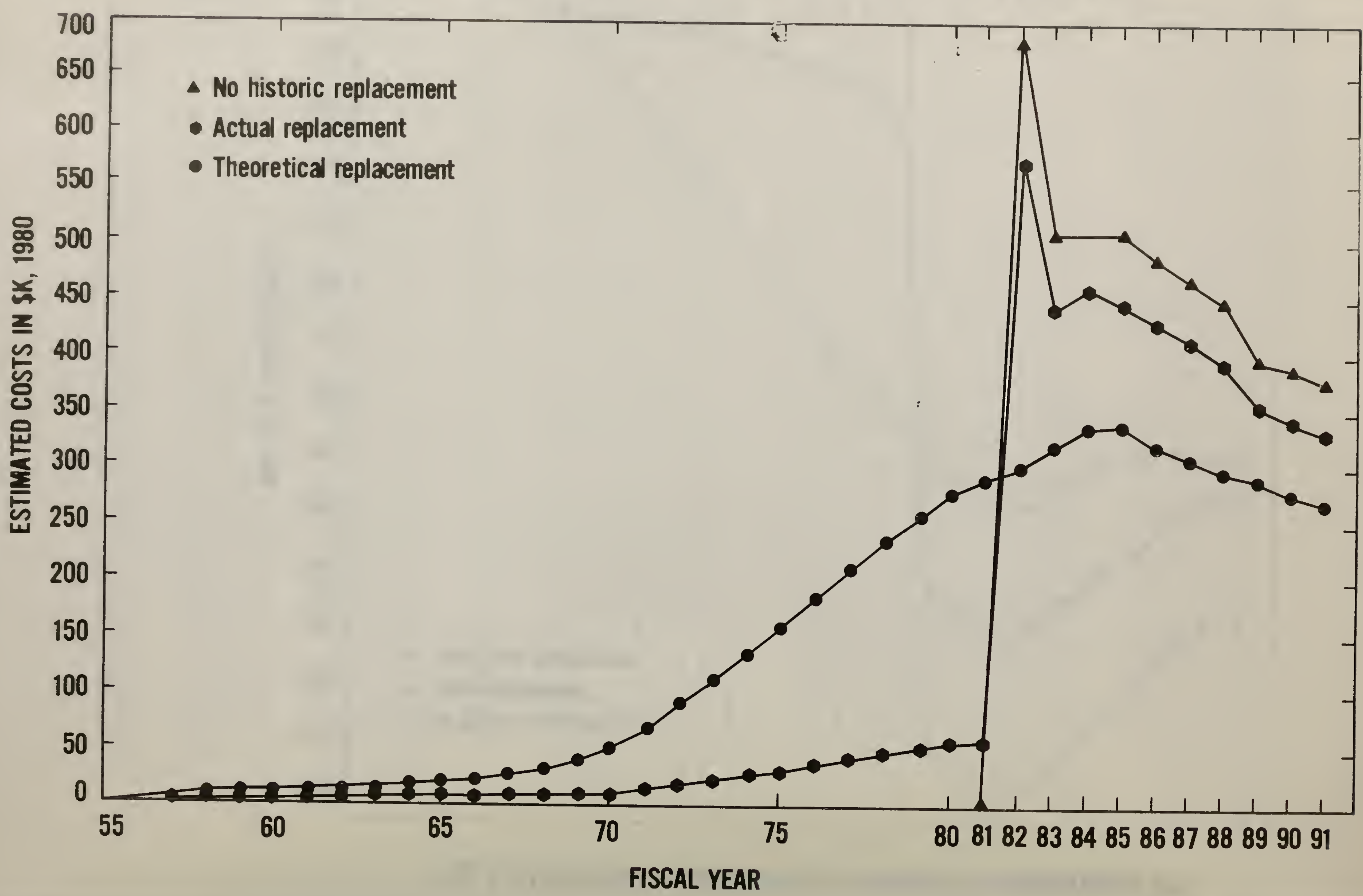

Table 2.5

Estimated Annual Replacement Costs in Thousands of 1980 Dollars: Gaithersburg Site

FISCAL YEAR	THEORETICAL REPLACEMENT	MOST LIKELY REPLACEMENT	NO HISTORIC REPLACEMENT
1982	896	1,133	1,427
1983	946	1,173	1,469
1984	991	1,207	1,503
1985	994	1,198	1,487
1986	953	1,145	1,417
1987	922	1,098	1,355
1988	900	1,067	1,312
1989	892	1,001	1,225
1990	899	973	1,187
1991	909	972	1,181

Table 2.6

Estimated Annual Replacement Costs in Thousands of 1980 Dollars: Boulder Site

FISCAL YEAR	THEORETICAL REPLACEMENT	MOST LIKELY REPLACEMENT	NO HISTORIC REPLACEMENT
1982	304	569	682
1983	320	442	506
1984	340	460	641
1985	342	449	509
1986	326	430	489
1987	311	413	468
1988	295	395	450
1989	288	352	398
1990	282	345	392
1991	272	332	378

figure 2.4 and for Boulder in figure 2.5. The vertical axis of each figure shows the expected annual replacement cost in 1980 dollars. The horizontal axis of each figure enumerates each of the fiscal years in the ten-year period beginning in FY82. Each expected annual replacement cost curve produced by the probabilistic cost model is designated by a hexagon, a circle, a triangle, or a square, indicating no delay, a one-year delay, a two-year delay, or a three-year delay, respectively.

The changes in the timing of the funds were designed to show that, unless a substantial increase in the level of equipment replacements is undertaken in the very near future, annual replacement costs will escalate rapidly. Although this result might be expected for the Boulder site, one would probably not expect to see a significant change for the Gaithersburg site.

The estimates associated with a one-, two-, or three-year delay in funding for both sites are based on a projected trend of current expenditure levels. These projected expenditures are shown in the respective columns of tables 2.7 and 2.8. For example, with a one-year delay, the projected expenditure for Gaithersburg is 280K in FY82 and 62K for Boulder. For a three-year delay, the projected expenditures are 280K in FY82, 281K in FY83 and 284K in FY84 for Gaithersburg and 62K in FY82, 65K in FY83 and 70K in FY84 for Boulder. If we define the first fiscal year in which the full replacement cost needed is allocated as the "first-year-replacement cost," we see that substantial increases in this figure occur for each site. Referring to table 2.8, it can be seen that the "first-year-replacement cost" for Boulder increases from 569K with no delay to 732K with a delay of three years. Perhaps what is most startling is the rapid increase in the "first-year-replacement cost" for the Gaithersburg site. Table 2.7 shows that although the Gaithersburg site is newer than the Boulder site, an increase in "first-year-replacement costs" of approximately 30 percent can be expected if the current level of funding is maintained over the next three years. Similar patterns are also revealed in tables 2.7 and 2.8 for "second-," "third-," and "fourth-year-replacement costs." One can thus conclude that the annual replacement costs for each site are very sensitive to any delays in the required level of funding for replacement expenditures. Note that the expected replacement cost for FY91 for a three-year delay at the Gaithersburg site exceeds the no delay cost figure by approximately 100K. Since such differences persist for some time into the future, the total replacement costs of the three-year delay will likely exceed those of the no-delay scenairo when considered over a longer period of time, say 15 to 20 years.

Fig. 2.4 Effects of funding delays on the Gaithersburg replacement cost schedule

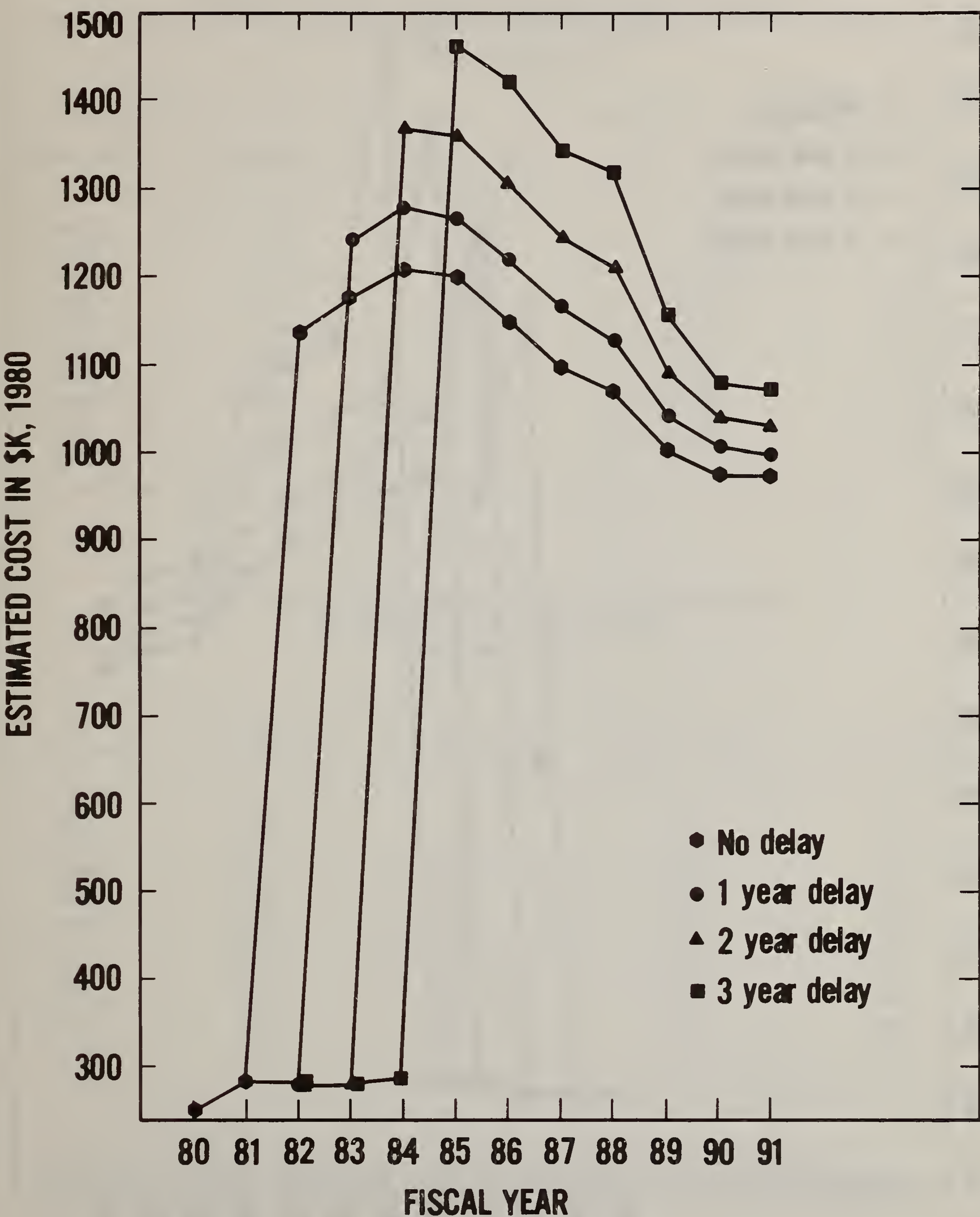

Fig. 2.5 Effects of funding delays on the Boulder replacement cost schedule

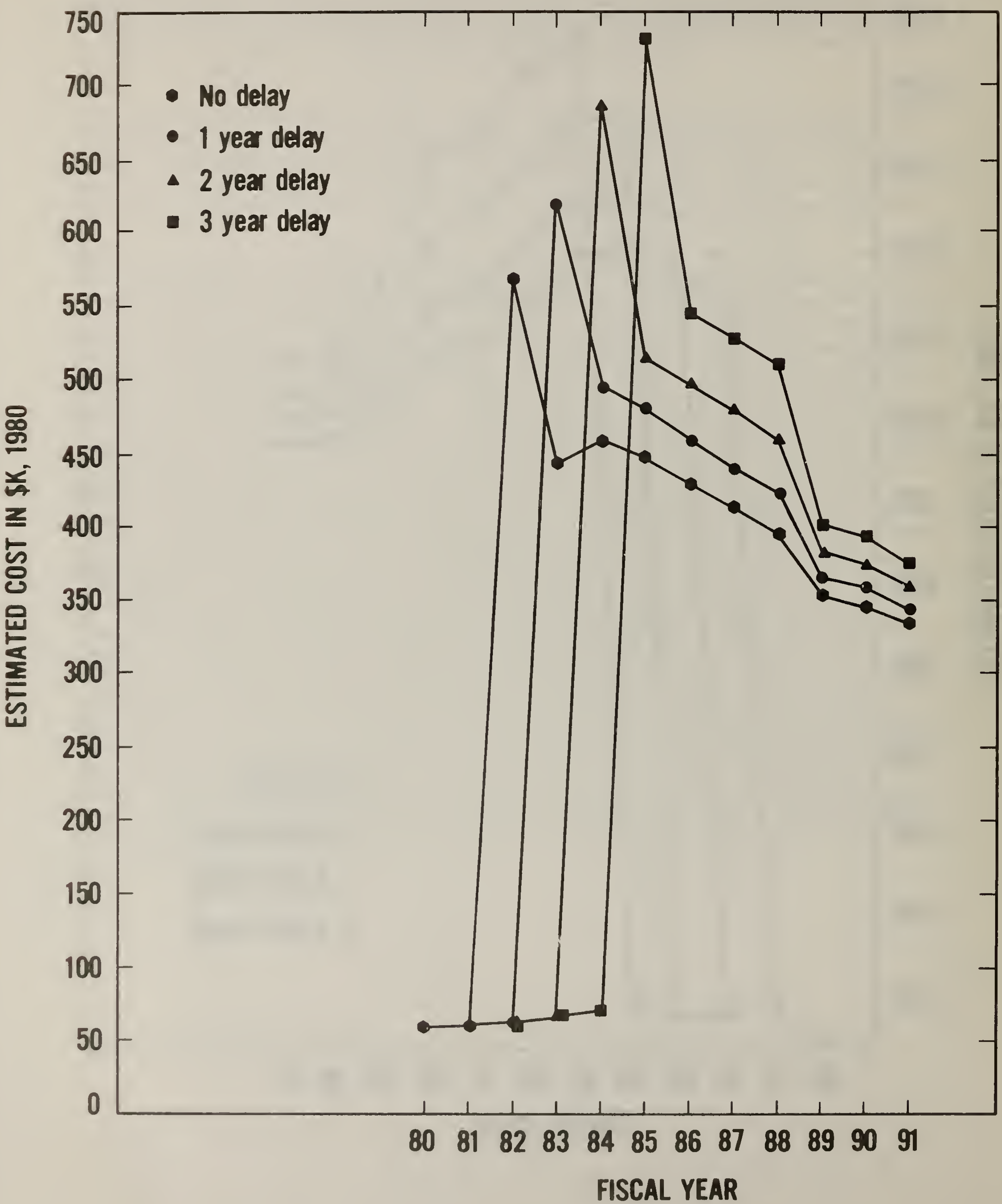

TABLE 2.7

MOST LIKELY REPLACEMENT COSTS OF VARIOUS DELAYS
IN THOUSANDS OF 1980 DOLLARS:
GAITHERSBURG SITE[a]

FISCAL YEAR	NO DELAY	1 YEAR DELAY	2 YEAR DELAY	3 YEAR DELAY
1982	1,133	280	280	280
1983	1,173	1,242	281	281
1984	1,207	1,277	1,365	284
1985	1,198	1,269	1,359	1,475
1986	1,145	1,217	1,307	1,425
1987	1,098	1,162	1,242	1,342
1988	1,067	1,128	1,208	1,309
1989	1,001	1,040	1,091	1,154
1990	973	1,002	1,037	1,085
1991	972	998	1,030	1,070

TABLE 2.8

MOST LIKELY REPLACEMENT COSTS OF VARIOUS DELAYS
IN THOUSANDS OF 1980 DOLLARS:
BOULDER SITE[a]

FISCAL YEAR	NO DELAY	1 YEAR DELAY	2 YEAR DELAY	3 YEAR DELAY
1982	569	62	62	62
1983	442	617	65	65
1984	460	495	685	70
1985	449	477	515	732
1986	430	460	498	546
1987	413	441	479	529
1988	395	423	461	511
1989	352	365	381	401
1990	345	357	373	394
1991	332	343	357	376

[a] The cost estimates presented in tables 2.7 and 2.8 do not include any additional operating or maintenance costs due to replacement delays.

3. SUMMARY AND RECOMMENDATIONS

3.1 SUMMARY

(a) For a ten-year period between FY82 and FY91, the estimates in terms of first quarter 1980 dollars for plant and facility equipment replacement at the NBS campuses are as follows:

BOULDER	GAITHERSBURG	TOTAL
4,187,000	10,967,000	15,154,000

(b) The annual estimates in terms of first quarter 1980 dollars for the above equipment replacement are:

FISCAL YEAR	BOULDER	GAITHERSBURG	TOTAL NBS
1982	569,000	1,133,000	1,702,000
1983	442,000	1,173,000	1,615,000
1984	460,000	1,207,000	1,667,000
1985	449,000	1,198,000	1,647,000
1986	430,000	1,145,000	1,575,000
1987	413,000	1,098,000	1,511,000
1988	395,000	1,067,000	1,462,000
1989	352,000	1,001,000	1,353,000
1990	345,000	973,000	1,318,000
1991	332,000	972,000	1,304,000
TOTAL	4,187,000	10,967,000	15,154,000

(c) The equipment service life concept, the cost factor model (manual procedure) and the probabilistic cost model (computerized procedure) are useful for this study.

(d) The engineering studies and economic principles and applications suitable for the identification and selection of plant equipment replacements in energy conserving and cost-effective ways are presented in appendices B and C. These appendices include the technical areas of equipment efficiency, computer simulation, thermal insulation, equipment control, solar energy, water conservation and life-cycle costing in which CBT is actively involved.

3.2 RECOMMENDATIONS

(a) Before any actual equipment replacement is scheduled, the appropriate engineering studies[1] should be performed. Life-cycle cost

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[1] See appendix B for a complete listing of studies relative to energy conservation.

techniques[1] should be used to ensure that the most cost-effective items are selected for replacement.

(b) Develop and maintain a data bank which will permit the validation and modification of equipment service lives actually experienced at the NBS campuses. In addition to providing information on equipment service lives, such a data bank would facilitate the process (either manually or via computer calculations) of identifying and pursuing more cost-effective levels of equipment maintenance.

(c) Update this study at least every five years to support the NBS budget planning process.

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[1] The discussion in appendix C is intended to establish broad guidelines as to how life-cycle cost techniques can be used to facilitate equipment selection and maintenance. Details of this approach, including a format for performing life-cycle cost calculations related to alternative equipment selection, maintenance and replacement programs, should be developed through consultation with the Plant Division.

APPENDIX A

INFORMATION SOURCES

A.1 SITE AND REPLACEMENT INFORMATION

a. Gaithersburg site:

(1) Information contained in the Preliminary Study of Planned Replacement of Plant and Facility Equipment at NBS Gaithersburg Site, NBSIR 78-1567, November 1978; and

(2) A request made by the Gaithersburg Plant Division on November 15, 1979, for the inclusion of fume hoods and related exhaust ductwork in this study.

b. Boulder site:

(1) Building Number 3, renovation and remodeling, an undated report;

(2) Space survey, cryogenic building, dated May 1965;

(3) Solar energy chemical dehumidification system research proposal, data April 7, 1975;

(4) Radio building HVAC study and appendix report, dated August 28, 1975;

(5) Feasibility study, improvements to the window systems, data May 18, 1976;

(6) Planning report, site utilization, dated January 5, 1977; and

(7) Coal conversion study, dated October 20, 1978.

A.2 SERVICE LIFE INFORMATION

a. Equipment service life statistics published in 1978 for discussion purposes only.[1] The discussion led to an approval to include the service life statistics in ASHRAE Transactions 1978, Vol. 84, Part 2. Table A.1 is by courtesy of ASHRAE.

b. Service life for underground piping, refrigerated compressors and boilers was obtained from Ricwil Corporation, York

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[1] Mustafa T. Akalin, "Equipment Life and Maintenance Cost Survey," ASHRAE Journal, October 1978.

Corporation and Union Iron Works, the manufacturers of the original equipment.

c. Service lives for roadway and parking lots were obtained from the Transportation Department of Montgomery County, Maryland.

A.3 ENGINEERING COST INFORMATION

The following engineering cost information was obtained for making estimates for equipment replacements:

a. Cost experiences and cost estimates of potential projects obtained from Plant Divisions at the Gaithersburg and Boulder sites;

b. Estimates for refrigerated compressors and boilers were obtained from York Corporation and Union Iron Works, the original manufacturers of the equipment; and

c. Mechanical and electrical cost data published by the R. S. Means Company.[1]

A.4 BUILDING OCCUPANCY YEAR

a. Gaithersburg site

BUILDING	OCCUPANCY YEAR	BUILDING	OCCUPANCY YEAR
101	1965	236	1968
202	1963	245	1964
206	1963	301	1964
220	1966	303	1964
221	1966	304	1964
222	1966	302	1963
223	1966	306	1963
224	1966	102	1970
225	1966	205	1974
226	1966	230	1969
231	1968	237/238	1968
233	1968	307	1972
235	1965	308	1969
		309	1975

Average occupancy year (weighted by floor area) = 1965

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1 Mechanical and Electrical Cost Data: 1979, Second Edition, Robert Snow Means Company, Inc., Kingston, Massachusetts, 1979.

b. Boulder site

BUILDING	OCCUPANCY YEAR
1	1954
2	1952
3	1952
4	1951
5	1951
21	1963
22	1964
24	1967
25	1966

Average occupancy year (weighted by floor area) = 1955

TABLE A.1

EQUIPMENT SERVICE LIFE STATISTICS[a]

EQUIPMENT ITEM	MEAN	MEDIAN	MODE(S)	PERCENTILES 25%	75%	N
UNITARY EQUIPMENT						
ROOM AIR CONDITIONERS (window or through-the-wall)	10	10	10	5	10	38
UNITARY AIR CONDITIONERS						
1. Air Cooled - Residential (Single Package or Split System)	14	15	15	8	20	29
2. Air Cooled - Commercial/Industrial (Single Package - through-the-wall or split system	15	15	15	10	20	40
3. Water Cooled - Electric	15	15	15-20	10	20	17
UNITARY HEAT PUMPS						
1. Air Source - Residential (Single Package or Split System)	11	10	10	10	12.5	12
2. Air Source - Commercial/Industrial (Single Package or Split System)	15	15	15	11	15	13
3. Water Source - Commercial/Industrial	13	13	10	10	20	8
COMPUTER ROOM CONDITIONERS	18	15	15	15	20	23
ROOF TOP HVAC SYSTEMS						
SINGLE ZONE Heating, Ventilating & Cooling or Cooling Only	15	15	15	10	20	30
MULTIZONE Heating, Ventilating & Cooling or Cooling Only	16	15	15	10	20	25
HEATING EQUIPMENT						
BOILERS						
1. Steam - Steel Watertube	30	26	40	20	40	30
- Steel Firetube	24	25	25	20	30	14
- Cast Iron	30	30	30	20	35	12
2. Hot Water - Steel Watertube	24	23	20	20	27	12
- Steel Firetube	23	24	30	17	30	16
- Cast Iron	30	30	30	20	40	13
3. Electric	14	15	15	7	17	9
BURNERS Gas - Forced & Natual and Oil-Forced	22	20	20	17	7	58
FURNACES Gas or Oil	18	20	20	12	20	35
UNIT HEATERS						
Gas or Electric	14	13	10	10	20	28
Hot Water or Steam	23	20	20	20	30	30
RADIANT HEATERS & PANELS						
Electric Heaters	11	10	10	5	25	6
Hot Water or Steam Panels	26	25	20-25	20	30	7
AIR HANDLING & TREATING EQUIPMENT						
TERMINAL UNITS						
1. Induction Units	26	20	20	20	30	16
2. Fan Coil	21	20	20	16	22	28
3. Diffusers, Grilles & Registers	35	27	20	20	50	26
4. Double Duct Mixing Boxes Constant or Variable Air Volume	21	20	20	15	30	20
5. Variable Air Volume (VAV) Boxes Single Duct	24	20	20	20	30	7
AIR WASHERS	20	17	30	10	30	6
HUMIDIFIERS	18	15	10	10	20	23
DUCTWOK	35	30	50	24	50	31
DAMPERS including Actuators	25	20	20	15	30	20

[a] SOURCE: ASHRAE

TABLE A.1

EQUIPMENT SERVICE LIFE STATISTICS (cont.)[a]

EQUIPMENT ITEM	MEAN	MEDIAN	MODE(S)	PERCENTILES 25%	75%	N
FANS (supply or exhaust)						
1. Centrifugal-Forward curve or Backward Inclined	27	25	20	20	40	43
2. Axial Flow	23	20	20	10	30	16
3. Wall Mounted - Propeller Type	17	15	20	10	20	15
4. Ventilating - Roof Mounted	17	20	20	10	20	22
HEAT EXCHANGERS						
COILS						
1. DX	22	20	20	15	27	21
2. Water or Steam	24	20	20	20	30	49
3. Electric	15	15	10-15-20	10	20	9
SHELL & TUBE	25	24	20	20	30	20
COOLING EQUIPMENT						
RECIPROCATING COMPRESSORS	18	20	20	12	20	7
CHILLERS-PACKAGED - Reciprocating	19	20	20	15	20	34
- Centrifugal	25	23	20	20	30	28
- Absorption	24	23	20	20	30	16
HEAT REJECTION EQUIPMENT						
COOLING TOWER - Metal-Galvanized	18	20	20	10	20	33
- Wood	22	20	20	15	27	25
- Ceramic	33	34	20	20	45	6
AIR COOLED CONDENSER	20	20	20	15	25	27
EVAPORATIVE CONDENSER	18	20	20	15	20	13
CENERAL COMPONENTS						
INSULATION						
1. Preformed - block, molded, etc.	27	20	20	20	30	43
2. Blankets, batts	29	24	20	20	40	23
PUMPS						
1. Circulating, Base Mounted	19	20	20	13	24	37
2. Circulating, Pipe Mounted	12	10	10-15	6	15	28
3. Sump & Well	15	10	30	6	30	25
4. Condensate & Receiver	18	15	15	10	25	25
ENGINES, TURBINES, MOTORS						
1. Reciprocating Engine	19	20	20	20	20	12
2. Turbines - Steam	30	30	40	24	30	13
3. Electric Motors	18	18	20	13	20	24
MOTOR STARTERS - Across Line or Magnetic	19	17	20	10	30	34
TRANSFORMERS						
Dry Type or Oil Filled	31	30	30	20	40	49
CONTROLS & INSTRUMENTATION						
1. Pneumatic	21	20	20	15	24	35
2. Electrical	17	16	20	10	20	24
3. Electronic	15	15	10-15	10	20	16
4. Automated (computer) Building Control Systems	22	20	20-25	10	25	8
VALVE ACTUATORS						
1. Electric	16	14	10-20-30	5	25	18
2. Hydraulic	15	15	20	5	24	8
3. Pneumatic	18	20	20	10	25	26
4. Self Contained	14	10	5-20	5	24	9

[a] SOURCE: ASHRAE

APPENDIX B

ENGINEERING STUDIES

This appendix includes a recommended list of engineering studies to determine if equipment replacement due to technical obsolescence or for reasons of energy conservation is necessary. The engineering results obtained from the recommended studies will be evaluated by the economic principles and applications outlined in appendix C of this report. The results of this economic evaluation will be useful in planning and justifying future costs for equipment at the time of its replacement.

B.1 GAITHERSBURG SITE

a. Energy Studies, Computer Simulation - Investigate and recommend energy and cost savings as determined by a computer simulation for the site distribution system.

b. Central Chillers, Computer Simulation - Investigate and recommend energy and cost savings as determined by a computer simulation for the central chillers.

c. Central Boilers, Computer Simulation - Investigate and recommend energy and cost savings as determined by a computer simulation for the central boilers.

An example of the need for the above engineering studies is that, based on past engineering performance data, the capacity of the existing central compressor and central boiler may be too large for cost-effective operation. Studies (a), (b) and (c) are proposed to determine whether to replace the pieces of equipment with the same capacity or with a smaller capacity.

d. Computerized Monitoring and Control System (CMCS) - Evaluate the existing CMCS in Building 223 and recommend how this CMCS can be extended to serve the entire Gaithersburg site including the impact of the CMCS on facility maintenance. Special attention is called to the possible need for computerized control of the boilers in Building 301 and for the fresh air in-take control of all buildings for conserving energy.

e. Solar Energy - Investigate and recommend whether solar energy[1] can be technically and economically added for supplemental heat. One possible use of solar energy is to provide for the reheat of HVAC during the summer.

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[1] Coordination is required between this proposed project and the Federal Solar Buildings Program which is being conducted by the Department of Energy (DoE). This program is funded at $100 million and established for Federal agencies to demonstrate the use of solar energy in existing Federal buildings.

f. Building Envelopes - Investigate and recommend whether additional insulation and storm windows should be provided for the building envelopes.

g. Waste Heat Recovery - Investigate and recommend the possible use of the wasted heat discharged through the boiler stacks in Building 302.

h. Planning Activities - Develop a five-year facility planning study responsive to the facility replacement need. It is recommended that the economic principles outlined in appendix C be included in this study.

i. Additional Studies - Subsequent to the above recommended engineering studies, in May 1979, the Plant Division developed a list of detailed studies divided into two groups: feasibility studies; and studies which are useful in determining plant equipment replacements due to technical obsolescence. These studies are listed as follows:

   A. Feasibility Studies

   1. Chilled Water, Total System - To examine the possibilities for energy conservation from operational and design changes of the system and to quantify the effects of these changes. This study should include:

      a. Optimum year-round chilled water discharge temperatures;

      b. Optimum size and drive possibilities for the fifth refrigeration unit;

      c. Changes of existing chiller components;

      d. Imbalance between central plant chilled water generation and site usage in spring, fall and winter, including the possibility of primary and secondary loops, either at single buildings or for groups; and

      e. Value of shutting off refrigeration unit on winter nights until the chilled water temperature reaches 50°F.

   2. Steam, Total System - To examine the possibilities for energy conservation from operational and design changes of the system and to quantify the effects of these changes. This study should include:

      a. Change to modern computerized controls;

      b. Optimum year-round operating pressures;

c. Waste heat recovery (stacks, deaerators and air compressors). Note: The Trane Company provided a proposal on the stacks to the Plant Division.

3. Air-Conditioning Unit (ACU) - Variable Air Volume (VAV) in Building 223 - Demonstrate the feasibility of the unit set up for VAV with the cooperation of Building 223 occupants and, if feasible, measure the savings.

4. Solar Heating - A feasibility study by the Design Engineering Office should be updated so as to satisfy DoE requirements.

B. Technical Obsolescence Studies

1. General Purpose Laboratories (GPL) Perimeter Air-Conditioning Unit (ACU) Shut Off - As soon as the demonstration (hopefully in Building 223) shows that this can be done, it should be presented to the Executive Board with a request for:

   a. Authority to operate GPLs on a nighttime and weekend partial shutdown schedule;

   b. Moving temperature sensitive operations out of the perimeter; or

   c. Justifying not doing so because of its impact on technical research.

2. Miscellaneous Retrofit or Modification of Air-Conditioning Operation - Review all ACU operations where they are run inefficiently [e.g., a unit is run continuously to condition 10 rooms, although out of hours it is only needed for 1 room. A unit is run continually when it should only come on out-of-hours if humidity rises (202) or temperature varies more than acceptable (library)].

3. ACU - VA Discharge Temperature (VADT) on Perimeters - Demonstrate with the Building 223 unit set up for VADT the possibilities (in the fall of 1980 when cold whether arrives) of allowing the supply air temperatures to rise and save cooling and improve comfort.

4. ACU Operation - Test units for correct operation and reduction of air stratification problems. Confirm best settings of avoidance of conflict between damper and coils.

5. Building Shells - Review insulation requirements in walls and roofs and value of changes in window design for energy conservation. Consider value of making Adminstration Building tower north side windows fixed; to be cleaned from

the outside, so as to reduce infiltration. Consider value of caulking for all buildings, especially those with large window exposure to the north.

6. Boiler Efficiency - Run test to establish efficiency.

7. RU Efficiency - Run test to establish efficiency.

8. CMCS Evaluation - Evaluate operation and recommend most beneficial extension areas.

9. Energy Audit - Follow requirements of DoE ten-year plan for audit. Consider the value of audits beyond those required by DoE.

10. RU Shut-Off - Follow the trend of winter RU load as changes in operations affect it, and continue to explore the shut-off possibility in conjunction with section (e) of study A.1.

B.2 BOULDER SITE

a. Centralized HVAC Systems - Investigate and recommend the possible use of centralized HVAC system(s) to replace many of the small systems in Building Number 1 and elsewhere. These studies should include work on the:

   1. Central Hydronic Systems;

   2. Wind Air Conditioning; and

   3. Delta Control System.

b. Building Envelopes - Investigate and recommend whether additional insulation and storm windows should be provided for the building envelopes.

c. Solar Energy - Investigate and recommend whether solar energy can be technically and economically added as a supplemental energy source, in view of the possibility that the DoE will fund the design and installation through the Federal Solar Buildings Program.

d. Planning Activities - Develop a five-year facility planning study responsive to facility replacement needs. It is recommended that the economic principles outlined in appendix C be included in this study. These studies should include:

   1. Current Space and Facility Utilization;

   2. Current Space and Facility Deficiencies;

3. Project Space and Facility Requirements; and

4. Evaluation of Options for Space and Facility Modifications and Acquisition.

e. Additional Studies - Based on the previous studies, it is recommended that the Boulder Plant Division develop a list of detailed engineering studies on specific projects.

APPENDIX C

ECONOMIC PRINCIPLES AND APPLICATIONS

C.1 ASSESSING THE SENSITIVITY OF THE BUDGET ESTIMATES TO CHANGES IN EQUIPMENT REPLACEMENT COST AND SERVICE LIFE

The purpose of this section is to provide background information on how a change in one or more of the key factors, other than the timing of funds for equipment replacement, will affect the annual and total replacement cost figures. In order to provide this information, a series of sensitivity analyses were performed. These analyses are designed to answer several specific "what if" questions. In principle, a series of "what if" questions could be applied to any factor; for example, item count or equipment age. However, since the information on item count and equipment age was deemed to be relatively reliable, it was decided to focus attention on variations in replacement cost and equipment service life achieved through alternative effective maintenance programs.

The second factor, effective maintenance program, recognizes the option that the Plant Divisions have to maintain items for a longer or shorter period of time than the original service life distribution would indicate prior to their replacement. It is important to point out that under this option there may be additional maintenance costs incurred by the Plant Divisions due to greater demands on the staff. These costs are not included in the estimates since they are staff rather than equipment oriented. Thus one should not jump to the conclusion that the best policy is to prolong indefinitely the useful life of a piece of equipment. As will be shown in appendix C.2, the increases in operating and maintenance costs associated with prolonged use may, beyond a certain point, rise faster than the reductions in replacement costs achieved through a prolongation of useful equipment life. A program of "effective maintenance" permits (at least in theory) the service life of a particular item to be extended beyond the period that would be expected with a normal maintenance program. The claim that an effective maintenance program is already in effect at both NBS sites can be supported by the relatively lower figures on past replacements across all items surveyed. The specific parameter values used in the analyses are summarized in table C.1.

From the table, it can be seen that under the most optimistic conditions replacement costs might be only 80 percent of those presented earlier. By the same token, under the most pessimistic conditions replacement costs might be 30 percent higher than those presented earlier. (Recall that all costs are in terms of first quarter 1980 dollars.) The ranges in replacement cost may seem rather large; however, they are designed to cover the "true" replacement cost. This is because the estimates used in this study are "ball park" in accuracy (i.e., $\pm$ 30 percent). By factoring all estimates up and down by roughly the outer limit of each estimate, however, we are almost certain to contain the true total replacement

TABLE C.1

Parameter Values Used in the Sensitivity Analyses of Equipment Replacement Cost and Service Life

FACTOR	PARAMETER VALUE	DESCRIPTION
Replacement Cost	0.80	Optimistic Cost Factor
	1.00	Expected Cost Factor
	1.30	Pessimistic Cost Factor
Change in Effective Maintenance Program	-1	Small Cutback
	0	Remains As Is
	2	Modest Improvement
	4	Significant Improvement

cost. The change in the effective maintenance program ranges fom a small cutback to a significant improvement. More specifically, a parameter value of -1 translates into a 1-year reduction (on the average) of the mode and end point in the service life distribution--that is, the year in which replacement is most likely to occur is moved up 1 year. Similarly, the year by which all equipment must have been replaced is moved up by 1. A parameter value of 2 implies an increase in the scope of the existing NBS maintenance program which postpones the year in which replacement is most likely to take place (the mode) by two years and by which total replacement must have taken place by 2 years. No estimates of the expected increase (if any) in the cost of maintenance staff or potential changes in operating costs are included, however.

The results of the two sets of sensitivity analyses for Gaithersburg and Boulder are presented in figures C.1 and C.2, respectively. The total expected replacement costs are shown along the vertical axes. The changes in the effective maintenance program are shown along the horizontal axes. A value of 0 on the horizontal axis represents no change in the effective maintenance program. Each figure contains three curves which roughly parallel each other. The curves labeled 1.3, 1.0 and 0.8 represent the level of total replacement costs as a function of the effective maintenance program under the pessimistic (1.3), expected (1.0), and optimistic (0.8) replacement cost scenarios, respectively. For example, under the pessimistic replacement cost scenario, if a small cutback in the effective maintenance program at Gaithersburg is pursued, total replacement costs are expected to be approximately $14.8 million over the ten-year planning horizon rather than the original $11.0 million estimated by the probabilistic cost model. In the event that costs behave as expected and the effective maintenance program improves modestly, then expected total replacement costs will fall from $11.0 million to $10.0 million. Under

Fig. C.1 Results of the replacement cost - sensitivity analysis for the NBS Gaithersburg site

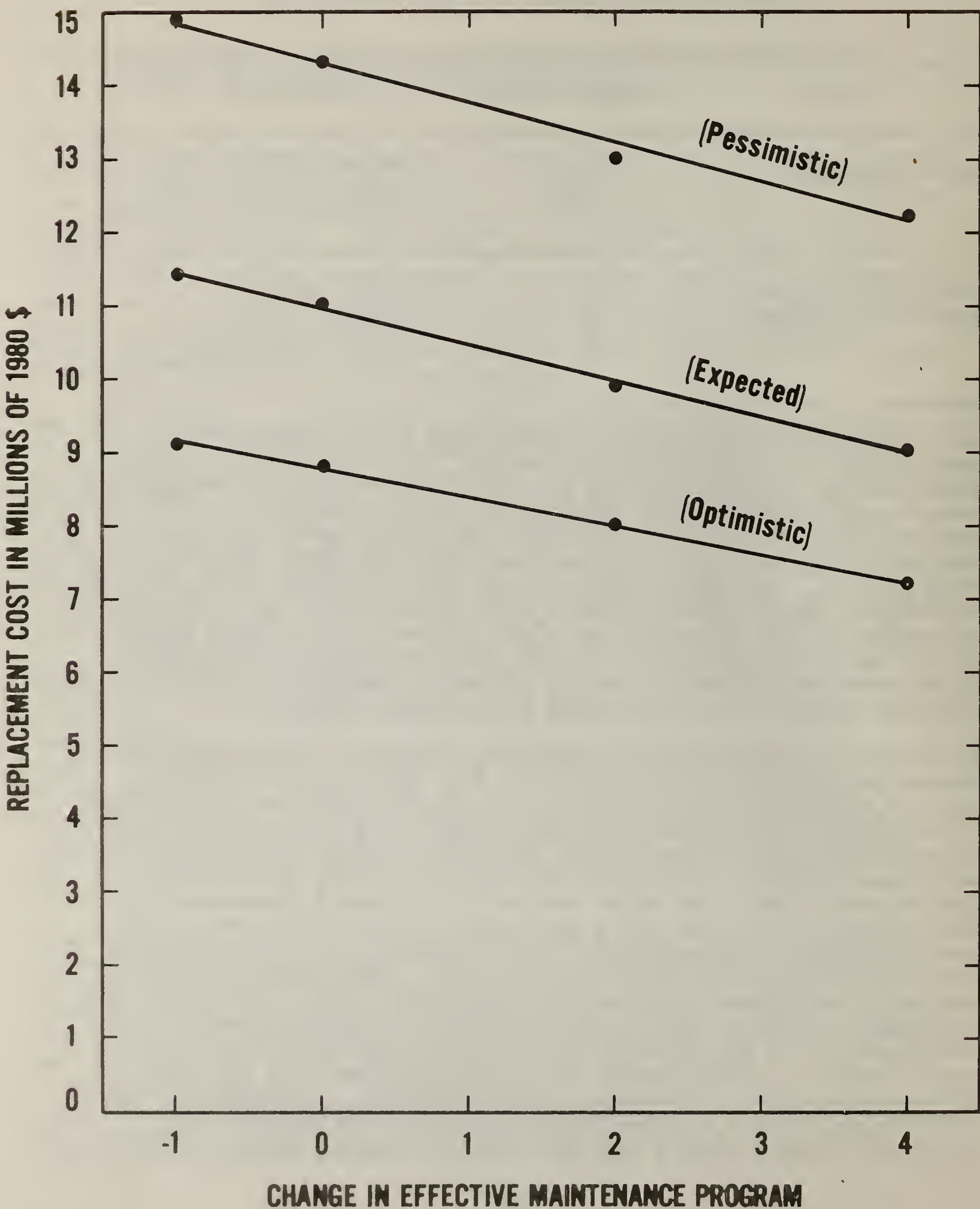
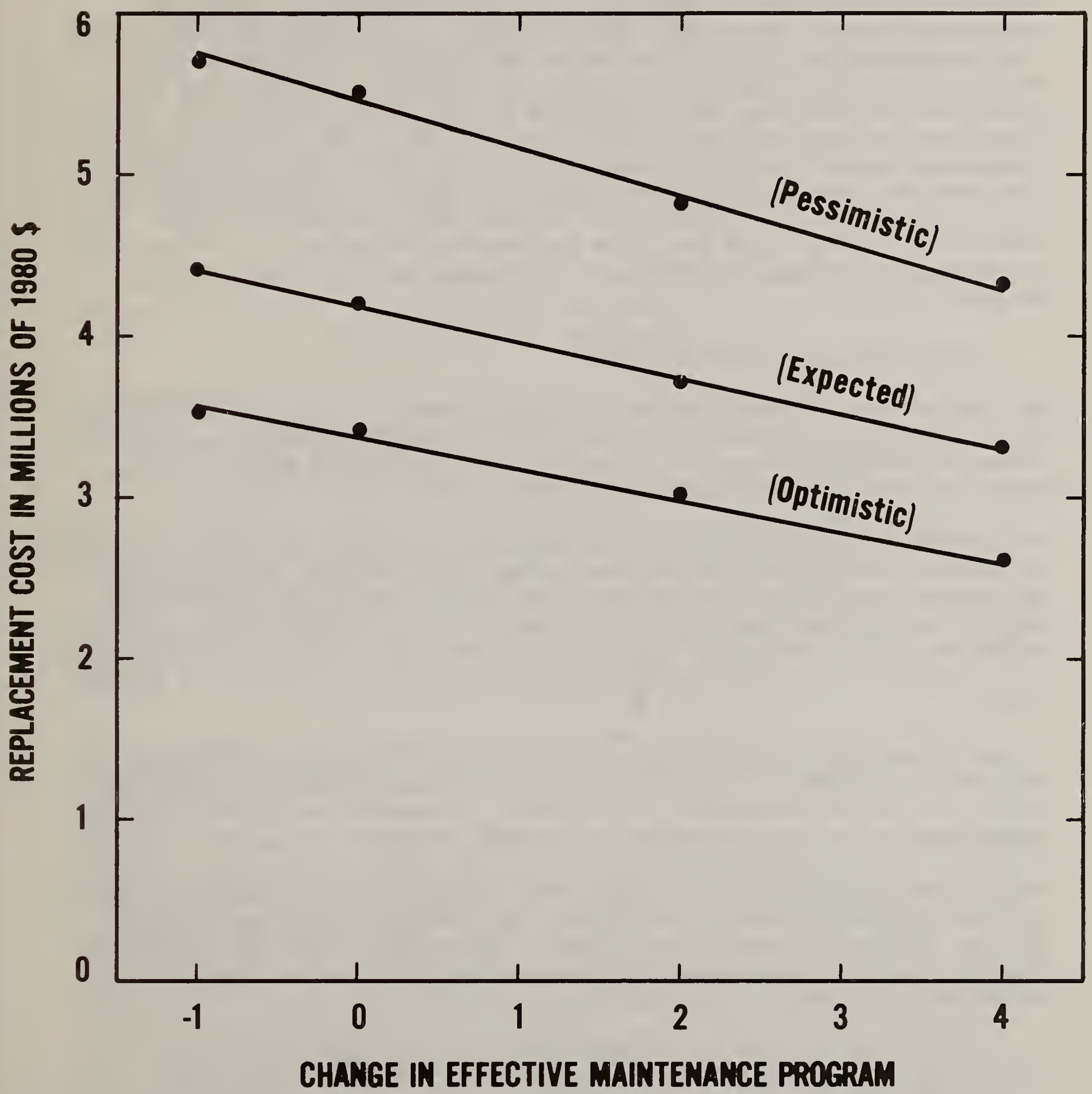


Figure C.2 Results of the replacement cost - service life sensitivity analysis for the NBS Boulder site



the optimistic replacement cost scenario, expected replacement costs may be as high as $9.1 million and as low as $7.2 million. The results for Boulder (See figure C.2) exhibit a similar trend.

The previous discussion serves to highlight the claim that, from a purely hardware viewpoint, relatively small changes in an "Effective Maintenance" program can be almost as important as large swings in the estimated replacement costs. Note that, since changes in the effective maintenance program (including its expected costs) and expected replacement costs are to some extent substitutes, it may be possible to balance the two costs so as to minimize the total costs of operating, maintaining, and repairing the physical plant. This does not imply that operating and maintenance costs should be ignored. However, the previous discussion does provide a rationale for not pursuing a single maintenance program to the exclusion of all others just because the alternatives differ somewhat from the status quo. The methodology behind such a "balancing" procedure, including life-cycle cost considerations, is outlined in section C.2.

C.2 LIFE-CYCLE COST CONSIDERATIONS

In this section, we shall review several economic concepts which permit us to identify a cost-effective equipment replacement program. In particular, we shall focus on how life-cycle cost techniques enable us to choose among alternative equipment types and maintenance programs.

Cost-benefit analysis provides the basic framework for an economic analysis of alternative equipment maintenance programs. That is, by the systematic weighing of available alternatives, cost-benefit analysis establishes guidelines for increasing the efficiency of resource allocation. The emphasis in this section will be on those portions of cost-benefit analysis which permit us to choose among effective maintenance programs of varying scales.

It was stated earlier that life-cycle cost techniques should be used at the time a component is replaced because they explicitly considered all costs over the study period. We now wish to examine how life-cycle cost techniques can be used to define an optimal equipment maintenance program.

Under ideal situations the optimal level of equipment maintenance (denoted hereafter as the effective maintenance program) may be defined through the use of several broad types of data. The actual procedure for calculating the life-cycle costs associated with the alternative effective maintenance programs is as follows:

(a) Identify the technically feasible alternatives;
(b) Identify the potential effective maintenance programs;
(c) Calculate the initial costs;
(d) Calculate the annual costs of the potential effective maintenance program;
(e) Select or develop a service life distribution;

(f) Select a planning horizon;
(g) Calculate the annual expected replacement costs using the service life distribution;
(h) Calculate the annual operating costs and maintenance based on the effective maintenance program; and
(i) Discount all future costs to a present valve.

It is important to point out that all but three of the above-mentioned steps have been thoroughly treated in this study. Although steps (b), (d), and (h) were not performed in this study, information on steps (b) and (d) was made available through ASHRAE. Information on step (h) could probably be constructed from past records maintained by the Plant Divisions. Information on steps (b) and (d) should also be available from the records of each Plant Division. This information would be more desirable than that from ASHRAE because it can be tailored to the specific mode of operation at NBS.

Of the nine steps outlined above, the last one, discounting, usually causes the most confusion. In particular, the selection of an inappropriate discount rate may result in serious problems.

A discount rate is defined as that rate of interest which reflects the time value of money. (The "time value" of money stems from the difference between the value of a dollar today and its value at some future time if invested at a stated interest rate. That is to say, a dollar today is worth more than a dollar in ten years, apart from inflation.) The discount rate may therefore be used to bring future costs back to the present so that all alternatives can be compared on an equivalent basis. Second, a real discount rate is one expressed in constant terms (i.e., current dollar values have been adjusted to take out the reduction in purchasing power due to inflation). Therefore, a real discount rate may be thought of as that rate which treats future costs and savings in terms of constant dollars.

For most Federal agencies the discount rate is fixed by the Office of Management and Budget. This figure is almost always a real rate. The rate is currently ten percent.

Another area where confusion often results is when prices are escalating. However, the use of a real discount rate serves to minimize this problem since, unless a cost is known to be increasing over the general rate of inflation, its current cost (e.g., in first quarter 1980 dollars) may be used as the cost in real dollars for some future period (e.g., second quarter 1984). This strategy, in essence, assumes that the cost of the item rises at the general rate of inflation. For some items, energy for instance, this assumption is not valid. More specifically, over the past several years energy prices have been increasing or escalating at a rate significantly over that of the general rate of inflation. Fortunately, fuel price escalation rates have been forecast by the Energy Information Administration over the three five-year periods beginning in 1980 and ending in 1995 (1980-85; 1985-1990; 1990-1995). For periods between 1995 and 2010 the fuel price escalation rates between 1990 and 1995 should be used. These figures are broken down by region, building type, and fuel type. They may be applied to the purchased energy cost figure to get the anticipated increase in energy costs over the remainder of the life cycle.

If the discount rate is denoted as D, the life cycle as L, the installation cost, C_o, and the costs for maintenance, repair or replacement in year t as C_t, the life-cycle cost of an equipment maintenance program, C, may be defined as:

$$C = C_p + \sum_{t=1}^{L} (C_t)/(1 + D)^t$$

In the case of energy costs, the life-cycle costs associated with the use of X units of energy at a cost of P_{1980} per unit may be expressed as:

$$E = \sum_{t=1}^{L} [(X) (P_{1980}) F(t)]/(1 + D)^t$$

where F(t) = the escalation factor through year t.

Returning once more to the earlier discussion, we see how life-cycle cost concepts may be used to define an optimal equipment maintenance program. Once steps (a) through (i) have been performed, two sets of curves for each technical alternative will emerge. The two sets of curves are:

(1) The expected costs of installing and periodically replacing the item; and

(2) The sum of the costs of operation and effective maintenance.

Both sets of curves may be plotted as a function of the level of effective maintenance.

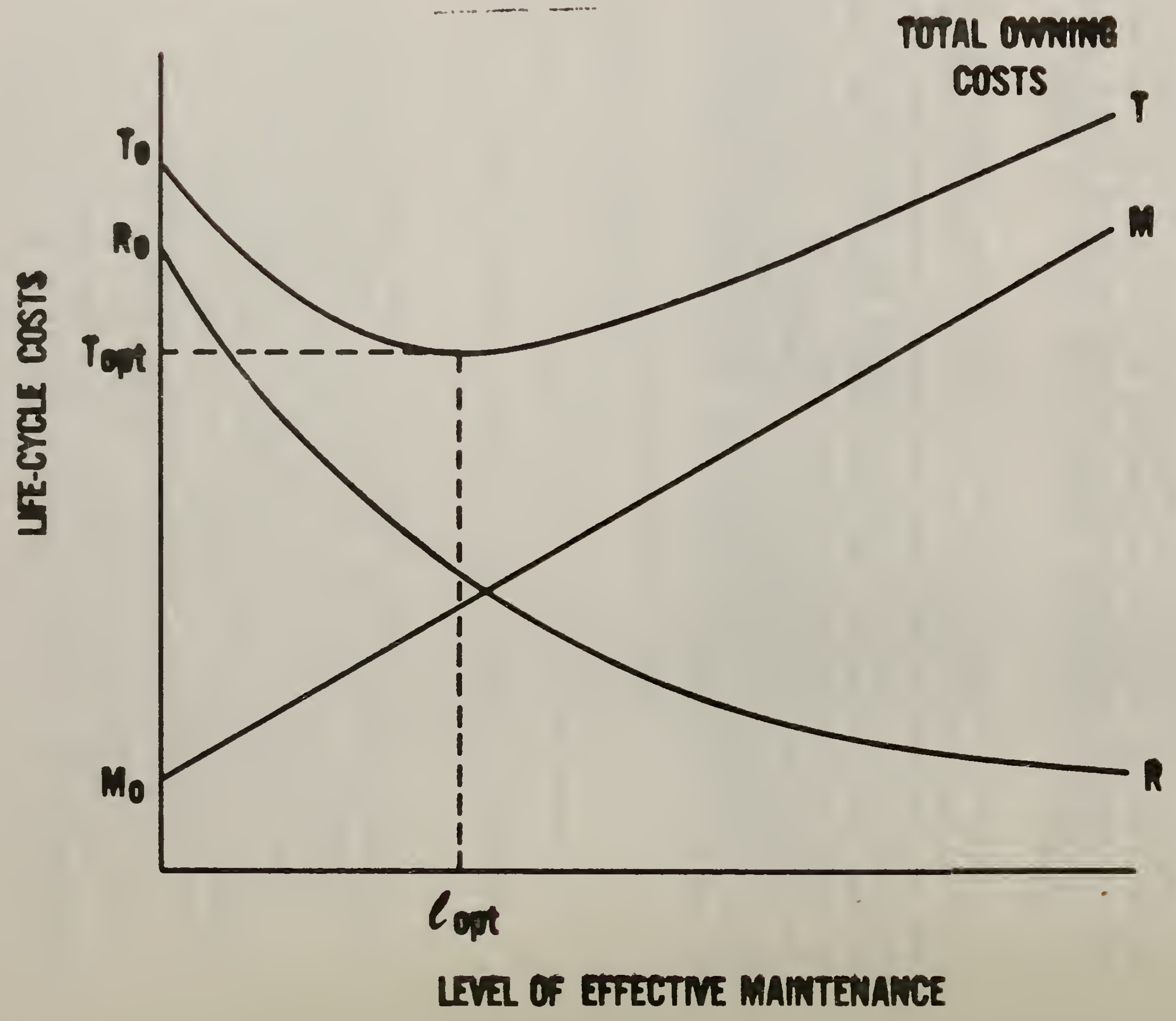
As the level of effective maintenance is increased, the expected costs of installation and repair are reduced. Since these costs contain substantial initial cost components, however, they do not fall linearly. This relationship must be recognized and incorporated in the calculation of life-cycle costs. Referring to curve R_oR in figure C.3, it can be seen that the life-cycle costs associated with a nominal maintenance level, R , are quite high. As the scope of the effective maintenance program is increased, life-cycle costs fall off quickly at first and then at a diminishing rate. Of course, if we are to count the <u>benefits</u> of reduced installation and replacement costs which accrue from a better effective maintenance program, we must also include all <u>costs</u> associated with that level of effective maintenance. These costs, the life-cycle costs of operation and maintenance, are illustrated graphically by the curve M_oM in figure C.3. The M_oM curve is illustrated as rising at a constant rate.

The choice must now be made as to how to tradeoff the costs of the effective maintenance program against reduced installation and replacement costs. If we vertically sum the two curves, we get the total life-cycle costs. Notice that this curve, T_oT, decreases to a minimum and then rises. At the minimum, T_{opt}, the total life-cycle costs are minimized. It is this effective maintenance program level, ℓ_{opt}, that is optimal because it minimizes the costs of owning and operating the system.

By a closer examination of the T_oT curve, it can be seen that at any point to the left of the point (ℓ_{opt}, T_{opt}) total costs could be reduced by increasing the level of the effective maintenance program. Similarly, at any point to the right of (ℓ_{opt}, T_{opt}) total costs could be reduced by decreasing the level of the effective maintenance program. Constraints can easily be introduced into this formulation. For example, if the optimal level of effective maintenance is not feasible, say due to a slot ceiling, then it would be possible to move leftward from ℓ_{opt} until the point where life-cycle costs subject to the ceiling constraint were minimized.

It is important to point out that in the previous discussion the level of effective maintenance was an abstract concept. Although one can assert that, as the level of effective maintenance increases from some nominal or minimal level, the total costs of owning and operating the system will decrease to a minimum and then rise indefinitely, it is not possible to say either how far above the minimal level of how far below the optimal level the current NBS programs lie. To determine the current level of effective maintenance at the NBS and those effective maintenance programs which are feasible in the engineering sense requires access to the data defined in the previous section.

FIGURE C.3 DEFINING THE LEVEL OF EFFECTIVE MAINTENANCE WHICH MINIMIZES LIFE-CYCLE COSTS



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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The replacement of aging plant and facility equipment is a major concern of all Federally owned and operated installations. Past efforts at equipment replacement have often underutilized information on the service life distribution of a particular component/system. More specifically, equipment was usually maintained until it either failed or reached some average age at which time total replacement was initiated.

This study develops a framework, based on service life distributions fitted to data from a published survey, for dealing with the "replacement problem." Service life distributions are used to develop replacement schedules for approximately 50 major plant and facility equipment items at the National Bureau of Standards (NBS) Gaithersburg and Boulder sites. The costs associated with these replacement schedules are estimated on an annual basis over a ten-year planning horizon using a probabilistic cost model. Estimates from this model are intended for use in budgeting for replacements over the planning horizon. The results of this study indicate that approximately $15 million (all estimates are in first quarter 1980 dollars) will be needed to meet expected replacements during fiscal years 1982 through 1991 at the NBS Gaithersburg and Boulder sites.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)

Building maintenance; cost engineering; economic analysis; rehabilitation cost.

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