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HIGH POWER MICROWAVE TUBE RELIABILITY STUDY

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August 1976

Final Report

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16. Abstract
This report summarizes the accomplishments on a program to collect, study, and analyze reliability data and to develop models based on these data that can be used to predict the reliability of microwave tubes.

The data were collected from the military services and various manufacturers for microwave tubes used in radar, communication and electronic counter measure systems. Included in the data were tubes from air, ground, and sea installations. The frequency range of the tubes in the data is 400 MHz through 16 GHz, and the peak output power of the tubes is generally over 100 watts.

Reliability models were developed for 70 tube types which may be used to predict failure rates and removeal criterion distributions. Additional reliability models were developed for klystrons, twystrons, magnetrons, traveling wave tubes, triodes and tetrodes which may be used to predict failure rates and removal criterion distributions based on operating parameters such as power, frequency and duty cycle.

A methodology was developed to determine tubes requiring reliability improvement based expenditures required to replace failed tubes.

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Magnetron	Reliability	
Traveling Wave Tube		
Twystron	Failure Rate	

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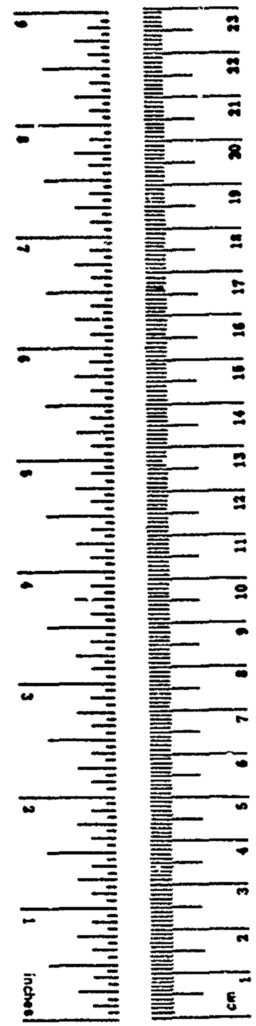
153 850 lpg

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

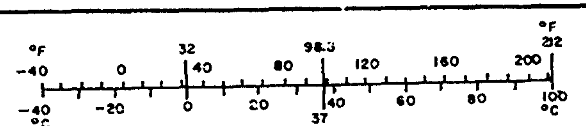
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

The "High Power Microwave Tube Reliability Study" under Contract F30602-74-C-0229 was conducted by the Engineering Experiment Station (EES) at Georgia Tech in conjunction with the School of Industrial and Systems Engineering (ISyE). The program was administered under Georgia Tech Project A-1532 by the Systems Engineering Division within the Applied Engineering Laboratory, Engineering Experiment Station. The program was under the direction of Mr. R. P. Zimmer, and under the general supervision of Dr. H. A. Ecker, Director of the Applied Engineering Laboratory.

This effort was sponsored jointly by the Federal Aviation Administration and the Air Force. The program was directly administered by the Techniques Branch of the Rome Air Development Center and responded to the guideline of the Reliability Branch which has the responsibility for updating the MIL-HDBK-217B. Mr. Patsy A. Romanelli was the Air Force Program Manager and worked in conjunction with Mr. John F. Carroll and Mr. Les J. Gubbins of RADC and Fred Sakate, Reliability Engineering Branch, Federal Aviation Administration.

EVALUATION

The purpose of this program has been to develop a mathematical model from which tube reliability can be determined. Failure of any tube that will result in the loss of system performance is costly. Therefore, consideration of tube reliability which can be predicted with confidence is necessary so that the system incorporating the tube can be properly designed to achieve its performance objectives. The prediction of reliability requires the use of a mathematical model that will reflect tube performance under various conditions of operation.

Patsy A. Romanelli

PATSY A. ROMANELLI
Project Engineer

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I. INTRODUCTION

Microwave tubes are major components of many communications systems, ECM systems, and most modern radar systems and a tube failure results, at least, in a partial system failure. Failures in systems are costly, and may degrade the capabilities of the user in such areas as military defense, air traffic safety, and hazardous weather warnings. Hence, a high degree of system reliability is necessary for both mission accomplishment and reasonable operating costs over the life of the system. With reliability data on tubes as well as other components of the system, the system may be designed to meet its cost-performance objectives, including sufficient back-up systems for continuous operation, estimates of operating costs, and the maintenance schedule. Also, inventory requirements for spare parts and purchase order sizes may be estimated using reliability data. To address the above needs for reliability information on high power tubes, this study had two main objectives.

The first objective was to assemble all available data relating to the reliability of microwave tubes of more than 100 watts peak power. These data were then to be analyzed to obtain estimates of tube failure rates thereby resulting in a data base that could be easily manipulated for additional data analysis. The second objective was to develop models describing tube reliability based on the data collected and analyzed. In addressing this objective, models of tube failure rates were developed for both individual tube types and general classes of tubes. The general tube classes included the klystron, TWT, magnetron, twystron, crossed field amplifier, amplitron, and gridded (triode and tetrode).

Reliability information of the above type is included in MIL-HDBK-217B, "Reliability Prediction of Electronic Equipment," which is in the process of being updated. This Handbook provides a common basis for predicting and comparing predictions on military contracts and proposals. Thus, one of the underlying goals of this study was to develop the models in a form suitable for incorporation into MIL-HDBK-217B. This goal provided guidelines in carrying out the various tasks as well as in establishing the format of the results.

The approach utilized in this study consisted of carrying out the following tasks outlined below.

1. Selection of tubes for study

   Inventory type tubes were selected which fit the power and frequency criteria, with a few exceptions.

2. Data collection on the selected tubes

   A search was made using various contacts available to Georgia Tech for all possible sources of microwave tube reliability data.

3. Data Analysis

   All data collected were analyzed to determine the reliability and failure mechanisms of the selected tubes

4. Model Development

   The reliablity and failure mechanism distribution of each tube within each general tube class were correlated with the tube operating parameters.

5. Cost-Reliability Analysis

   Cost, reliability and projected demand were used to identify tubes needing reliability improvement.

With the above approach, the models developed can also be useful in determining potential research areas for reliability improvement, system maintenance requirements, and user operational requirement in addition to the application of MIL-HDBK-217B toward proposals and contracts. Each of the above tasks has been accomplished, and are described in detail in the following sections.

II. TUBE SELECTION CRITERIA

A. Tube Types

Since the objectives of the program were to establish failure rates for microwave tubes and to construct models for predicting reliability, it was desirable to include as many different types of tubes as possible that are in common use. At the outset of the program, it was hypothesized that relationships exist between tube reliability and operating parameters such as power and frequency and further, that the general tube structure also influences reliability. Consequently, it was desired to collect data representing as many different general classes of tube structure as possible. The tube classes included in the data base were klystrons, twystrons, travelling wave tubes, magnetrons, crossed field amplifiers, amplitrons, and gridded tubes (triodes, tetrodes, etc.) Within each class, all tube types for which data could be obtained were considered for inclusion.

Since tube reliability depends on a number of factors, emphasis was placed on not only including tube structure and operating parameters as factors in the models but also environment and application.

Initially, the tubes to be included in the data base were selected on the basis of power, frequency and available data.

B. Power Level

An objective of the study was to determine the reliability of high cost tubes. Since the Department of Defense (DoD) and the Federal Aviation Administration (FAA) were searching for ways to reduce spending on tubes. By identifying tubes with high cost and poor reliability, additional efforts (if determined to be cost-effective) could be dedicated toward reducing the cost or improving the reliability of identified tubes.

High power tubes are typically high cost (above $10,000) for several reasons. A large capital investment, dedicated equipment, and highly qualified personnel are required for the design and manufacture of high power microwave tubes. Often special designs are used to achieve specifications unique to a particular application. Further, production of relatively small-volume orders also tend to keep the cost of microwave tubes at a higher level than lower power tubes. Also, because of the periodic demand for tubes, often some degree of re-tooling is necessary even to replenish a supply of tubes.

In general tubes with a kilowatt of peak or average power were desired for inclusion in the study; however, certain exceptions were made to the minimum power selection criterion. Reliability data on tubes of lower power were collected and analyzed giving a larger data base and, therefore, more confidence in the validity of the models developed.

C. Frequency Range

The frequency range of the tubes to be included in the data base was limited to the microwave range. Generally, tubes in S through K_u band were desired for inclusion in the data base; however many of the high power tubes for which reliability data were available were designed for use in L band (including the lower portion of the L band near 400 MHz).

As the available data were gathered it was discovered that little useful quantitative data for tubes in the K_u band existed. For this reason the upper bound on the frequency of tubes included in the study was in the K_a band.

D. Availability

Inventory type tubes were desired for inclusion in the data base as opposed to R & D type tubes. The assumption was made that R & D tubes are manufactured under highly controlled conditions in small quantities and that the field operation of R & D tubes is also under more control than a tube which is no longer in the R & D stage. The above assumption leads to the conclusion that the observed reliability of the R & D tubes is influenced by the highly controlled manufacturing and operation. The phrase "inventory type tube," therefore, refers to tubes which have completed the R & D phase (i.e. initial introduction in the field) and not necessarily an off-the-shelf item.

E. Environment

The environment in which a tube operated in general affects reliability. Microwave tubes typically employed in the following environments:

1. Ground based systems
    a. Fixed installations
    b. Mobile installations
2. Sea going systems
3. Airborne systems
4. Spacecraft systems

Reliability varies with environment because certain limitations are placed on systems due to size and weight constraints. Size and/or weight limitations are placed, to different degrees, on all systems except fixed ground based installations. Mobile ground based and seagoing systems have minimum restrictions, spacecraft systems the maximum and airborne system restrictions typically lie between the two. The size and weight constraints limit the amount of protective and monitoring equipment that can be incorporated into a system even if cost were not a factor. In addition, all of the tubes in systems other than the fixed systems are subject to various degrees of vibration which tend to fatigue the components of the tubes.

Reliability data were analyzed for tubes in all of the above environments except those used by spacecraft systems since these tubes typically are low power and did meet the minimum power criterion of the program.

F. Application

Microwave tubes are used in several applications. The applications considered in the study were (1) radar, (2) communications, and (3) ECM. It was assumed that most tubes types would be found in these three applications. Data on tubes used in linear accelerator applications were available and utilized in the study. Other applications such as laboratory research were not considered to fall within the scope of the program.

G. Selected Tubes

Data were solicited from the Air Force, Army, Navy, FAA, and various power tube and system manufacturers. Excellent cooperation was received from all of these sources and their assistance in providing data is gratefully acknowledged. For a variety of reasons, the data from the Air Force were significantly more useful for analysis and modeling purposes than the data from other sources. More data were available from the Air Force than from other sources. As a result, the data are principally from land based radar and communications systems. Other data are from airborne and sea-going environments and ECM applications. From this data base, tubes were selected that satisfied the selection criteria described above with limited modifications required to increase the number of tubes to be analyzed. Over seventy tube types were included in the analysis and modeling and are listed in Table II-1.

TABLE II-1 SELECTED TUBES

Tube/System Number	Tube Type	Manufacturer	Tube/System Number	Tube Type	Manufacturer
3KM300LA	Klystron	Varian	3KM3000LA	Klystron	Varian
3K210000LQ	Klystron	Varian	4K3CC	Klystron	Varian
4KM170000LA	Klystron	Varian	VA888E	Klystron	Varian
VA853	Klystron	Varian	4K3SK	Klystron	Varian
8824	Klystron	RCA	4670	Klystron	RCA
8825	Klystron	RCA	8568	Klystron	RCA
8826	Klystron	RCA	ZM3038A	Klystron	GE
3KM50000PA1	Klystron	Varian	L3250	Klystron	Litton
3KM50000PA2	Klystron	Varian	Z5010A	Klystron	GE
3KM50000PA	Klystron	Varian	SAC42A	Klystron	Sperry
4KM50LB	Klystron	Varian	X780D	Klystron	Varian
4KM50LC	Klystron	Varian	L3035	Klystron	Litton
4KM50SK	Klystron	Varian	VA842	Klystron	Varian
4KM50SJ	Klystron	Varian	L3403	Klystron	Litton
4KM50000LR	Klystron	Varian	4KMP10000LF	Klystron	Varian
4KM50000LQ	Klystron	Varian	VTR5210A1	TWT	Varian
4K50000LQ	Klystron	Varian	ZM3167	TWT	GE
3K50000LA	Klystron	Varian	MA2001A	TWT	Microwave Assoc.
3K50000LF	Klystron	Varian	VA138D	TWT	Varian
VA800E	Klystron	Varian	WJ3751	TWT	Watkins-Johnson
VA856B	Klystron	Varian	M5768	TWT	Teledyne-MEC
4KM3000LR	Klystron	Varian	VA643	TWT	Varian
3K3000LQ	Klystron	Varian	ALQ94 LB	TWT	*

*Multiple Vendors

TABLE II-1 SELECTED TUBES (CONTINUED)

Tube/System Number	Tube Type	Manufacturer	Tube/System Number	Tube Type	Manufacturer
ALQ94 HB	TWT	*	5586	Magnetron	Amperex
ALQ94 MB	TWT	*	8798	Magnetron	Raytheon
ALQ101 MB	TWT	*	7256	Magnetron	Raytheon
ALQ101 LB	TWT	*	VA913A	Twystron	Varian
ALQ117	TWT	*	VA145H	Twystron	Varian
ALQ117 HB	TWT	*	VA145E	Twystron	Varian
ALQ119 HB	TWT	*	VA144	Twystron	Varian
ALQ119 MB	TWT	*	7835	Triode	RCA
ALQ119 LB	TWT	*	2041	Triode	RCA
QK338A	Magnetron	Raytheon	6952	Tetrode	RCA
QK327A	Magnetron	Raytheon	QK681	Amplitron	Raytheon
400615	Magnetron	Cardion	SFD261	CFA	Varian

*Multiple Vendors

III. DATA COLLECTION

To establish as wide a data base as possible for the study, data on a variety of high power microwave tubes were solicited from a variety of sources. These sources included the Air Force, Navy, Army, the Federal Aviation Administration (FAA) and most tube and system manufacturers.

The Air Force has a well-established, well-defined field failure reporting system for tubes used in land based systems. A tube status reporting system exists for these same systems. The status reporting system contains the time accumulated on individual tubes in the field. A description of these reporting systems are contained in Technical Order TO-00-20-8 ("Inspection System, Documentation, and Reporting for Ground Communications-Electronics-Meteorological (CEM) Equipment" [1]). Because of the detail contained in this system, a reasonable estimate of the failure mode for each reported tube failure can be made. This reporting system is managed by Sacramento Air Logistics Center, Material Management Directorate, Item Management Division, Reliability Branch (SM-ALC/MMIRM) and the Engineering Division, Material Analysis Branch (SM-ALC-MMEAM) at McClellan AFB, California which provided excellent cooperation in both supplying data and explanation of questions which arose concerning the data. The data pertains principally to tubes used in ground based radar and communication system installations at Air Force bases throughout the world. A second Air Force failure reporting system is maintained by Warner Robins Air Logistics Center at Robins AFB, Georgia. The reporting system at Robins was established to determine current demand rates for equipment used in aircraft. The demand rates observed over a two year period are used to predict future demand rates. The demand rates are reported in failures per 100 flight hours only for recoverable (repairable) equipment. The determination of whether an item is repairable is based on the cost of the item. Therefore, most of the tubes in the reporting system are those used in ECM systems. The cost of most of the tubes in the airborne radar systems are below the cutoff defined by item management for recoverable equipment, and therefore, most radar tubes are not in the reporting system. Personnel at Robins AFB were very helpful with the data gathering effort.

Based on discussions with personnel at the Naval Ship Engineering Center, Norfolk Division, data from the 3-M system (Maintenance Material Management) were obtained for the SPS-48 system. These data covered a period from January 1970 to December 1974 and included replacement of all parts, not just microwave tubes. Some additional data were provided that indicated the number of operating hours for these systems. The Naval Weapons Support Center at Crane, Indiana supplied data on the CFA, TWT and switch tube used in the AGEIS system. These data were useful in determining the effects of a sea-going environment on tube life.

Data obtained from manufacturers were in general of only limited usefulness for several reasons. The cost of extended life testing of high power tubes is very high due to the investment required for the test setup and to the high cost of the tubes themselves. Since the manufacturers are not required nor paid to do this type of testing, the amount of available life test data were minimal. In addition, these tests may or may not reflect the operating conditions encountered in field use of the tube, therefore, the life of a tube observed in a life test is not the same as that experienced in field use. Manufacturers do perform compliance testing on a sampling of tubes using statistical quality control techniques. These tests are performed to insure that the requirements of the applicable Military Standard are being met. However, these tests usually are of limited duration or consist of repeated on/off cycling of the tube. An example of these type of data is shown in Table III-1. Table III-1 indicates

TABLE III-1 EXAMPLE MANUFACTURER'S LIFE TEST DATA

Tube Number	Type	Number Tested	Number Failed	Length of Test (hours)
6BM6A	Klystron	168	5	500
4J52	Magnetron	177	8	500
6543	Magnetron	86	7	400
7208B	Magnetron	33	15	500
7950	Magnetron	44	2	250
8855	Magnetron	21	1	1250
6344	Magnetron	13	3	1000
2J55	Magnetron	5	0	500
7256	Magnetron	15	1	892
6410A	Magnetron	10	1	400
7529	Magnetron	5	0	518
6517	Magnetron	3	0	250
SFD352	Magnetron	118	5	200
SFD342	Magnetron	28	0	600
SFD356	Magnetron	29	0	252
SFD370	Magnetron	7	0	1307
SFD377A	Magnetron	3	0	1533
BLM198	Magnetron	8	0	541
5780	Magnetron	10	0	1158
7452A	Magnetron	10	0	350
SFD261	CFA	10	5	Complete*

*Tubes tested until failure

that generally only a limited number of tubes were tested, the test times are relatively short compared to the expected life of the tubes, and very few or no failures were reported.

Some field failure data were available from RCA on several gridded tubes and klystrons. One of these (the 7835) was also included in the McClellan AFB data base. Raytheon provided field failure data on a twystron and TWT used in the SAFEGUARD systems. These data included both failed and unfailed (censored) tube reports with indication of cause of failure. These data were analyzed to determine the estimate of mean life, taking into account the censored data.

Of the data supplied by the military, the FAA, and the manufacturers, the data obtained from the Air Force were the most useful for the purposes of analysis and modeling. Data obtained from the Navy and several tube and system manufacturers were utilized to a lesser extent in modeling tube reliability.

The field failure reporting system used by the Air Force as described in TO-00-20-8 is useful for analysis and modeling because of the information reported on each tube failure. For each reported tube failure, the following data are supplied by the site personnel:

Tube type

Tube serial number

Equipment serial number in which the tube was installed

Squadron

The channel and socket in which each tube was installed

Date on which the tube was installed

Date on which the tube was removed

Number of filament hours

Number of hours below 90% power

A failure symptom code

A reject code

An environment code

A corrective action code

The number of months the tube was on the shelf before being installed

Tube manufacturer

In addition, the site personnel can provide any narrative comments needed to further explain the circumstances under which the tube failed or any of their observations. An example of the reporting form is shown in Figure III-1 When this report is processed at SM-ALC, an additional failure code, the Tentative Technician code is assigned based on information contained in the field failure report including the narrative comment. This code is an attempt to identify the actual cause of failure rather than any effects which might be identified by the symptom, reject, or environment codes. If the tube is covered by a repair contract, the tube is then shipped to the repair contractor for disposition. The repair contractor then submits a report indicating their opinion as to the cause of failure. Based on this report and the data from the field personnel, a Final Technician Code is assigned by personnel at SM-ALC. The Final Technicial Code was not available in most of the data from McClellan because this code has only been assigned to recent failures. All of the information from the field personnel (excluding the narrative comment) and the Tentative and Final Technician (when assigned) Codes are contained in the Tube Failure Report produced quarterly by SM-ALC for each tube in the reporting system.

1. TO:	ELECTRON TUBE FIELD LIFE RECORD					
SMAMA (MMPM) McClellan AFB, CA 95652	2 COMMAND: ADC	3. SUBCOMMAND: 24ND/AD	4 INTER COMD: 24AD	5. REPT. ORG.: 786	6. EQUIP TMS: FPS27	7. TUBE TYPE: ZM3038A

8. SERIAL NUMBER	9 MFR/REPAIRER	10. DT. FIRST INSTL	11. DT. OF FINAL FAIL	12. SHELF TIME (MOS)	13. FIL. HRS (TOTAL)	14 HIGH VOLTAGE HRS. (TOTAL)	15 RADIATE HOURS (TOTAL)	16. TOT RAD HRS BELOW 90%
425R1	GE	02/ 05/ 73	25/ 05 /73	2	540	504	479	0

17. SYMPTOMS	18 REJECT CRITERIA	19 ASSOC FAC.	20. CORR ACTION	21 WARRANTY ACTION	22 REPL. TUBE S.N	23. REPORT NO.	24.	25	26
AA	ZX	ZY	NA	1	509R3	0004			

INSTALLATION HISTORY

DATE INSTALLED A.	EQUIPMENT SERIAL NO B.	CHANNEL C.	SOCKET D.	DATE REMOVED/FAILED E.	FILAMENT HRS EA. INSTL F.	HIGH VOLTAGE HRS. EA. INSTL. G.	RADIATE HOURS EACH INSTALLATION H.	RADIATE HOURS BELOW 90% I.	REASON FOR REMOVAL J.	SUPERVISOR'S SIGNATURE K.
020573	0031	B	1	250573	540	504	479	0	Tube failed	Joseph Salu

27. REMARKS

Block 17: Code BD also applies.

Block 18: All meter readings, high voltage and RF drive were normal, however, the tube would not meet minimum power out on the majority of frequencies.

28 SIGNATURE AND GRADE OF REPORTING INDIV.	29 DATE	32 FROM (REPORTING UNITS COMPLETE ADDRESS)
Robert E Mortensen Jr TSGT	300573	786 Radar Sq (LGKQ) Minot AFS, Max, NDak 58759
30 SIGNATURE AND GRADE OF CEM MAINT SUPVR	31 DATE	
Lloyd M. Hess Jr, Lt Col	300573	

AFTO FORM OCT 70 120 PREVIOUS EDITION WILL BE USED.

Figure III-1 AFTO FORM 120, "Electron Tube Field Life Record."

The reports from SM-ALC were the primary source of data for the analysis performed. SM-ALC also produces several other reports such as the Failure Analysis Report which is described in detail in TO-00-20-8. Printouts of all Tube Failure Reports and Tube Status Reports in the McClellan AFB data base were provided by SM-ALC. The failure and status reports contained all data through December 1974. These reports covered different periods for different tubes depending on the year a particular tube type was introduced into service. For some tubes, the failure reports extended as far back as 1963 while others covered the period from 1969. There was also a large variation in the number of failures reported for each tube. The variation in the number of reported failures is attributable to factors such as the number of systems in service using that tube, the amount of time the systems were in service, and the mean life of the tube. Some tubes had as few as four reported failures while others had in excess of 1000 failures, with the largest number being approximately 3100.

Many failures occuring before 1972 have not been assigned a Tentative Technician failure code. Based on discussions with several tube manufacturers and SM-ALC personnel, it was decided that the Tentative Technician code was the most accurate of the codes available (recall the Final Technician code was generally unavailable) as an indication of failure causes rather than failure effects. Thus, before the pre-1972 data could be included in the Georgia Tech data base, a Tentative Technicial code had to be assigned to each failure where it was missing. This was assigned after examination of all data available on the Tube Failure Report, using best engineering estimates of the most probable cause of failure. The cause of failure cannot be positively identified for all of the reported failures. The failure modes reported in the data have been interpreted as the removal criterion for reasons discussed later in this report.

The Georgia Tech data base for the analysis consisted principally of data derived directly from the Air Force Tube Failure and Status Reports. For each failure, the following data were entered:

Tube type

Squadron number

Radiate hours at time of failure

Shelf time (in months) before installation

Georgia Tech failure code

Number of repair cycles

The three digit Georgia Tech failure code corresponds approximately to the two letter Tentative Technician Failure Code made by SM-ALC. For the tube status and failure reports through 31 December 1974, there were a total of approximately 12,000 failures and installations reported for the fourty-nine tube types being analyzed. The number of failures and installations per tube type ranged from a low of four to a high of 3200.

Data from the other sources were also added to the data base. Some of these additional data contained individual failure times and modes which could be entered into the data base with the same format as the data from McClellan. The remainder of the data contained only the observed failure rate for specific tube types. These latter data were not used in the data analysis but were combined with the results of the data analysis and used to develop the reliability models.

Several different computer programs were utilized in the analysis of these data. The first allows the analyst to select from the data base all failures in a particular squadron, all failures with a particular amount of shelf life, or all failures with a particular three digit failure code. Thus if the analyst wants to examine the effect of shelf time in excess of 60 months but less than 72 months on the mean life of the tube due to gassy removal criteria, he can select only those failures with shelf time between 60 and 72 months which have a 130 series (130-139) failure code. This flexibility and rapid selection capability proved to be invaluable for analyzing tubes with a large number of failure reports. A second computer program was developed to perform hazard analysis of the data. A third program combined the first two allowing automatic data analysis of all tubes in the data base. The third program, based on a run-time defined criterion, would select various sub-populations (including the total population) from the data for each individual tube type and perform hazard analyses on each sub-population selected. The sub-populations were based on the reported failure mode. The nature of the above programs are discussed in more detail in Section IV-B.

The structure selected for two of the models to be developed during the study included the failure rate of tubes failing for each of several failure modes and the frequency of occurrence (importance) of the respective failure modes. Therefore, it was necessary to collect and analyze data containing an indication of the failure mode and radiant hours for each failed tube.

One aspect of analyzing the reliability of microwave tubes is the assignment of a failure mode to each tube failure. Determination of failure modes was necessary to assess the importance of each failure mode to overall tube reliability. Identification of critical failure modes can lead to product improvement and extended lifetime, thus reducing costs.

An important point in the analysis of tube reliability is the effect of the system on tube reliability. A failure or malfunction in the system can cause catastrophic failure of the tube. Thus, some effort was made to distinguish between tube attributable and system attributable failures. It proved impossible and undesirable to make this an exact process because of the complex interactions between the tube and system, and the tube failure reports often indicated failure effects rather than causes. Thus, a chain reaction of failures which could occur in a tube sometimes results in only the last or most obvious failure mode being reported. Since many problems can be either a cause or an effect it would be necessary to have as much information as possible about the conditions surrounding the failure. Often this information was not available because it was not recorded at the time of failure. Consequently, assessment of failures only resulted in an estimate of the resultant removal criterion rather than an exact assessment of failure mode.

Different organizations use different methods of designating the failure mode of a tube, it was necessary to design a system which would be compatible with the data from the military services, the FAA, and the manufacturers. The primary differences in the failure code systems, other than using different letters or numbers to represent the same failure mode, is the degree of detail. Some systems give only a very general description of the reason the tube failed, while others are very detailed. One system, for example, might just indicate that there was an internal short while another would indicate the specific parts of the tube that were shorted. To accomodate the variety of detail present in the data, a three level, three digit failure mode coding system was devised. The first digit indicates if the failure is considered tube attributable (1), system attributable (2), or undetermined (3). The second digit is used to indicate subcategories of tube or system attributable failures. There are seven subcategories of tube attributable failure modes and seven of system attributable failure modes. Within each of these subcategories, specific failure modes are identified. A listing of all failure mode codes is given in Table III-2. An additional code not shown in the table is 000 indicating an installed and operating tube or a spare tube.

During the data collection and analysis phase of the project, discussions were held with various personnel involved with the failure reporting systems. Based on these discussions, the failure modes in the data and, therefore, in the models should be interpreted as the removal criteria resulting from an unidentified failure or malfunction either in the tube or system. The removal criterion given in the data and models is the reason the tube was removed from the system and the reason the tube cannot be returned to service. For example, if a power supply surge caused the tube's filament to melt, then the melted filament removal criterion, obviously, does not necessarily indicate a tube related failure cause; consequently, it does not necessarily indicate any specific failure cause because a failure or malfunction at some point in the system (including the tube) may place in motion a chain of events causing damage to some other component (possibly the tube), which probably would not have failed at that time under other circumstances. The models presented in Section VI of this report indicate the field experience with system (including the tube) failures or malfunctions resulting apparently in a damaged tube. The failure rates used to develop the models were based on the radiant hours accumulated on individual tubes when removed from a system. Each removal was assumed a failure regardless of the actual cause. Therefore, the failure rates presented in this report may, in general, be interpreted as removal rates.

TABLE III-2

FAILURE CODES FOR TUBE ATTRIBUTABLE FAILURES

Filament Failure	110
Heater Short	111
Shorted Heater to Other Element	112
Open Filament	116
Low Emission	120
Low Power Output	121
Sublimation	122
Failed Minimum Gain Check	123
Poor Spectrum	124
Low Anode Current	125
Failed Noise Figure Check	126
Cathode Depletion	127
Gassy/Loss of Vacuum	130
Cathode Bushing Leak	131
Misc. Weld/Braze Leaks	132
Slightly Gassy (10^{-5} Torr)	133
High Gas Pressure (>10^{-3} Torr)/High Ion Pump Current	134
Metal/Ceramic Leak	136
Bell Housing Leak	137
Window Failures	140
Window Leak/Corrosion	143
Tuning Mechanism/Mechanical Failure	150
Tuner Failure (Tracking Rate)	151
Mechanical Wearout	152
Leaks in Tuner Vanes	153
Excessive Tuner Torque	155
Focus Coil/Body Short	172
Improper Focus Coil Alignment	173
Focus Coil Defective or Open	174
Coolant leak on or within tube	197
Undetermined	366
Handling/Packaging	368

TABLE III-2 (continued)
FAILURE CODES FOR SYSTEM ATTRIBUTABLE FAILURES

Oil System Failures	210
Punctured Cathode Bushing	213
Pulse Transformer Failures	215
Punctured Heater Seal	235
Window Arcing	241
Multipactoring	242
Window Damaged/Burned	244
Window Cracked	245
Tube Casualty	260
Radiation Damage	261
Tube Frozen	262
Internal Arcing	263
Internal Short	264
Elements Warped	265
Power Associated Failure	267
RF Drive Improper	268
Magnetic System Failures	270
Magnetic Distortion	271
Collector to Body Short	275
Waveguide System Failures	280
Waveguide Arcing	281
Arcing in External Cavities	282
Improper Output Coupling	283
High VSWR	284
Pressure Regulation/ Hydrator Failure	285
Cooling System Failures	290
Coolant Leak	291
Clogged Passages	292
Restricted Airflow	293
Heat Exchanger	294
Low Pressure Interlock Failures	295
High Temperature Interlock Failure	296

IV. DATA ANALYSIS METHODOLOGY

A. General Reliability Considerations

1. Definitions and Concepts of Reliability

The reliability of a tube is defined as the probability it will perform its intended functions for a stated period of time. According to this definition the reliability of a tube may be shown as the probability of survival plotted as a monotonic decreasing function of hours of use. Figure IV-1 illustrates this relationship. Hours of use could be interpreted as either radiant hours or filament hours (radiant plus stand-by hours). Careful consideration was given to both interpretations early in the study and discussions were held with Air Force personnel concerning which would be the more appropriate time measurement to use in the analytical models. The concensus of opinion was that radiant times would be more suitable both because of the nature of the available data and the anticipated use of the models.

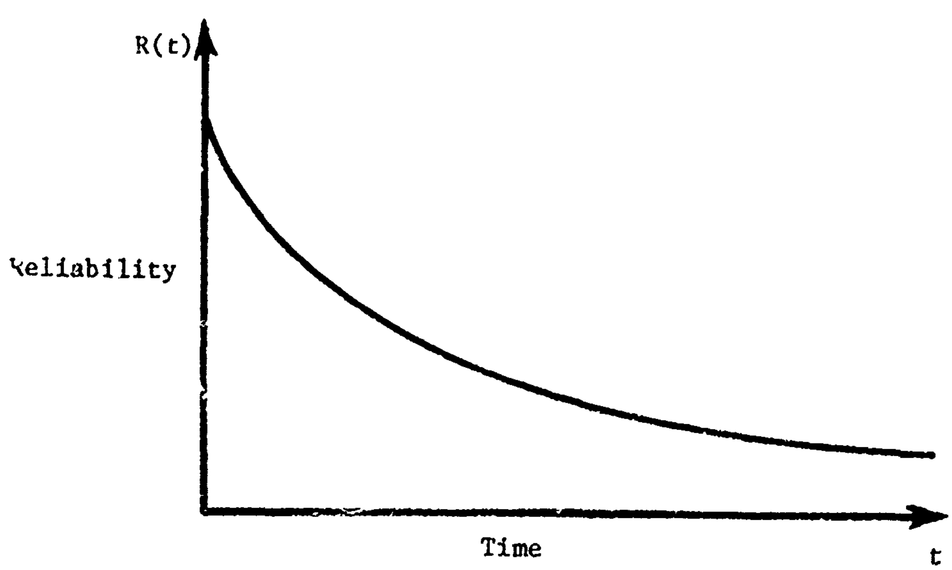


Figure IV-1 Example Reliability Function

A key parameter associated with the probability of survival is the mean time to failure (MTTF) or mean life. The reciprocal of this mean life is usually called the failure rate. If the distribution of failure times is exponential this mean life, or failure rate, is an accurate measure of tube reliability because the failure rate is constant over time for this distribution. For the exponentail failure distribution the mean life is the time at which 63.2 percent of the tubes will have failed. MIL-HDBK-217B expresses reliability in terms of the failure rate and therefore emphasis in this study was placed on assessing the tube failure data in terms of the failure rate.

If the failure distribution is something other than exponential the failure rate will be changing over time and its interpretation becomes more difficult. This situation occurs most frequently when tube wearout becomes a factor. The time at which wearout occurs varies among the tube types considered in this study. In Figure IV-2 the plot of failure rate versus operating hours illustrates this point. The initial (decreasing failure rate) period is usually

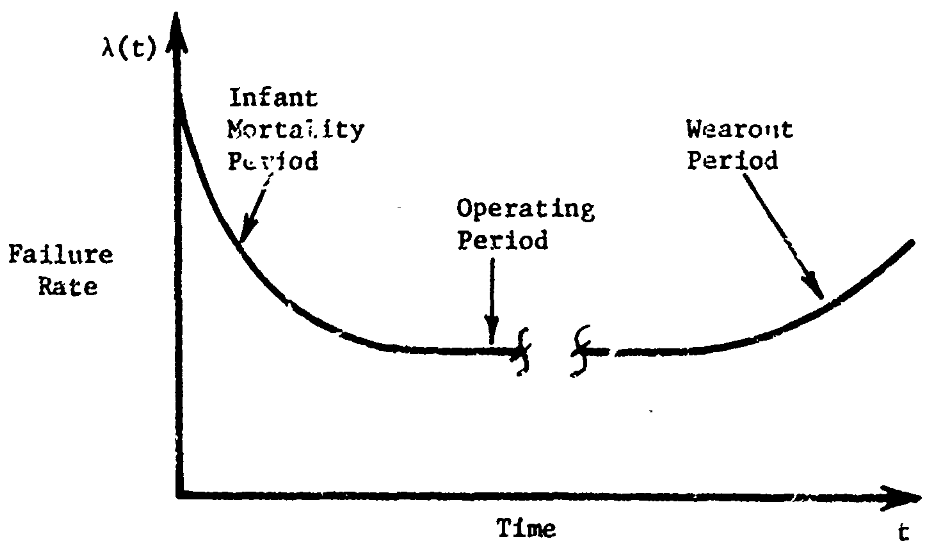


Figure IV-2 Tube Life Cycle

called the infant mortality period. During this period failures generally are of a quality control nature. Such early failures should be screened out from the data if a good measure of tube reliability is to be determined. No satisfactory method exists for dealing with reliability measures which include these "early failures". It should also be pointed out that instances of decreasing failure rate may be caused by mixed populations of tubes containing different failure rates. This situation may occur for tubes for which reliability growth is a factor and tubes made during different time periods.

The middle portion of the curve is a period with a relatively constant failure rate. This is the period when the exponential distribution is most likely to apply. Failures during this time period occur at relatively random intervals and are due to factors which can neither be attributed to wearout nor to quality problems. The failure rates for most tubes studied in this project were found to be approximately constant over this time period. This portion of the time period is considered to be the "operating period".

The third portion of the curve has an increasing failure rate due to age or wearout problems. Along with the infant mortality failures, failures attributable to wearout should be eliminated before a tube failure rate is determined. If tubes are to be described by their failure rate or mean life, the center or operating portion of the overall tube life pattern is the only portion that should be considered.

During the course of the study operational and wearout failures were analyzed with a set of computer programs. Points at which wearout failures occurred were identified and the data were again evaluated using the computer programs which separate the data into these two (operating and wearout) portions. Separate failure distributions were obtained for each portion of the data. Details of these procedures will follow.

2. Exponential Failure Distribution

If the mean life is relatively constant over time the appropriate distribution is the exponential. This distribution is of the form

$$f(t) = (1/\theta)e^{-t/\theta} = \lambda e^{-\lambda t}, \text{ for } t > 0 \qquad \text{(IV-1)}$$

where $f(t)$ = the probability of tube failure at time t

θ = meantime to failure or mean life

λ = failure rate = $1/\theta$

As mentioned previously this distribution is usually appropriate for modeling the failure distribution for the operating portion of the failure rate curve.

3. Weibull Failure Distribution

In cases where the failure rate was not constant the Weibull distribution was used in this study. This distribution is more general than the exponential in that it can fit regions of decreasing failure rate (infant mortality), relatively constant failure rate (operating period), or increasing failure rate (wearout). The two parameter Weibull was used in all cases. The density function for this distribution is as follows:

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-(t/\alpha)^{\beta}} \qquad \text{(IV-2)}$$

where α is the characteristic life or scale parameter and β is the shape parameter. The value of α is the 63.2 percentile point, i.e., 63.2 percent of the failures in a data set occur before time α. This parameter corresponds approximately to the mean life of the exponential distribution. For $\beta = 1$, the distribution becomes an exponential and α would be the mean life, θ.

4. General Probability Concepts

The density functions, $f(t)$, discussed above define the probability of failure at time t. The cumulative distribution function, $F(t)$, is used to describe the probability of failure at any time prior to time t. That is,

$$F(t) = \int_{0}^{t} f(x)dx \qquad \text{(IV-3)}$$

The reliability function, R(t), is the probability of survival to time t, or

$$R(t) = 1 - F(t) \qquad \text{(IV-4)}$$

As discussed previously, tube reliability may be described by this function or by the failure rate. The reliability function is a more accurate method for non-exponential data since for these situations the failure rate is not constant over time. A graph of the reliability function typically will have the form shown in Figure IV-1.

5. The Hazard Function

The Hazard function, h(t), is the instantaneous failure rate at time t, or

$$h(t) = f(t)/[1 - F(t)], \ t > 0 \qquad \text{(IV-5)}$$

As this expression indicates, h(t) is the probability of failure at any time t divided by the probability of survival at least to that time. It, therefore, is often treated as the **instantaneous** failure rate. For the exponential distribution the hazard function is constant. It is decreasing for infant mortality and increasing for wearout conditions.

The cumulative hazard H(t) is the integral of the hazard function up to time t.

$$H(t) = \int_{0}^{t} h(x)dx = -\ln[1 - F(t)] \qquad \text{(IV-6)}$$

Thus we may write

$$F(t) = 1 - e^{-H(t)}$$

or

$$R(t) = 1 - F(t) = e^{-H(t)} \qquad \text{(IV-7)}$$

This last expression gives the probability of survival to time t in terms of the cumulative hazard. Thus, for the cumulative hazard, H = 100% corresponds to the cumulative probability value of

$$F(t) = 1 - e^{-1.0} = .632 \text{ or } 63.2\% \qquad \text{(IV-8)}$$

This means that the cumulative hazard value of 100% corresponds to the mean life for an exponential distribution or the characteristic life for the Weibull and is in fact the 63.2 percentile point for any failure distribution.

For the exponential distribution recall that

$$F(t) = 1 - e^{-t/\theta}, \; t > 0 \qquad \text{(IV-9)}$$

$$f(t) = (1/\theta)e^{-t/\theta}, \; t > 0 \qquad \text{(IV-10)}$$

where θ is the mean life. The hazard function therefore is

$$h(t) = f(t)/[1 - F(t)] = 1/\theta, \; t > 0 \qquad \text{(IV-11)}$$

which is constant over time. The cumulative hazard is

$$H(t) = \int_0^t (1/\theta)dx = t/\theta, \; t > 0 \qquad \text{(IV-12)}$$

From this expression it can be seen that time to failure, t, as a function of H is

$$t(H) = \theta H$$

Thus time to failure is a linear function of the cumulative hazard and will plot as a straight line passing through the origin on linear graph paper. The slope of the line is the mean life and it may be found as the time corresponding to the value of 1.00 for H.

For the Weibull distribution recall

$$F(t) = 1 - e^{-(t/\alpha)^\beta}, \; t > 0 \qquad \text{(IV-13)}$$

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-(t/\alpha)^\beta}, \; t > 0 \qquad \text{(IV-14)}$$

The hazard function is thus

$$h(t) = \left(\beta/\alpha^\beta\right)t^{\beta-1}, \; t > 0 \qquad \text{(IV-15)}$$

which is a power function of time t. As previously mentioned, the hazard function increases with time for $\beta > 1$ and decreases for $\beta < 1$. For $\beta = 1$ it is constant and is equal to $(1/\alpha)$. The cumulative hazard is

$$\int_0^t h(t)dt = \left(\beta/\alpha^\beta\right)\int_0^t t^{\beta-1}dt \qquad \text{(IV-16)}$$

$$H(t) = \left(\frac{t}{\alpha}\right)^\beta, t > 0 \qquad \text{(IV-17)}$$

The time to failure, again expressed as a function of H, is

$$t(H) = \alpha H^{1/\beta} \qquad \text{(IV-18)}$$

Taking logarithms of the above gives

$$\ln(t) = (1/\beta)\ \ln(H) + \ln(\alpha) \qquad \text{(IV-19)}$$

Thus t will plot as a straight line function of H on log-log graph paper. The slope of the line is $(1/\beta)$ and the value of t for H = 1.00 is α.

B. Analysis Tools/Computer Program

All tube results were put on punched cards to be used for data input. There were two basic computer programs developed for use on this study. These were NEWHAZ and NEWMIX. Both of these programs can be used for either complete failure data or incomplete (censored) data. They are run on an interactive mode and also produce hard copy plots on a CALCOMP plotter.

The first program sorts the data by failure and censoring time. It then computes the hazard and the cumulative hazard values for each failure. For the exponential distribution, the cumulative hazard is then plotted against failure time using linear coordinates. A least squares straight line fit through the origin is then determined and this line is plotted over the hazard plot. The failure time corresponding to a cumulative hazard of 100% is computed from this least squares fit and printed on the plot as the mean life. The program then performs a goodness of fit test as discussed in the next paragraph to determine the appropriateness of the exponential distribution for the data. The program computes the natural logarithm of both the cumulative hazard and the failure times. They are then plotted as a Weibull hazard plot on another graph with logarithmic coordinates. Once again a straight line least squares fit is determined and plotted on the graph. The reciprocal of the slope of this line is computed and the result printed as the value of β, the Weibull shape parameter. The time corresponding to a cumulative hazard of 100% is computed from the least squares fit and this value is printed on the graph as the characteristic life, α. Once again a goodness-of-fit test is made where applicable.

There were two different goodness-of-fit tests available in the program to test the fit of the hazard data to the exponential distribution. The first was a Kolmogorov-Smirnov test which was used for data consisting entirely of failed tubes. That is, no tubes were censored (still operating at the latest reading time). The Kolmogorov-Smirnov test is not applicable, however, for data containing some tubes which have not failed (censored data) since it deals necessarily with maximum departure of the observed cummulative distribution from the theoretical exponential distribution, the entire failure distribution must be known. Therefore a second goodness-of-fit test was introduced into the program which is used when the failure data are incomplete, i.e. contains some censored tubes. This test is due to Gnedenko, et al. and is found in their text [2]. A discussion of the test is also found in the test by Mann, Schafer and Singpurwalla [3].

In the case of the Weibull distribution, as discussed above, the important question is whether the two parameter or three parameter Weibull distribution is applicable. The Weibull is only used when the exponential fit has been rejected. The third Weibull parameter is the location or threshold parameter.

Assuming it to be zero assumes that tubes can fail at any time after they are first turned on. Although these assumptions seemed reasonable it was felt that a test of it was desirable. Such a test was developed by Mann and Fertig [4]. This test is also discussed briefly in the test by Mann, Shafer and Singpuwalla. If the exponential is appropriate for the operating period, the mean life is approximately equal to the computed characteristic life.

In two cases use of the hazard plotting technique was found to be inappropriate for determination of mean life. The two cases are as follows:

1. A data set where the number of failed tubes is less than the number of surviving tubes will result in an abnormally high mean life calculation using hazard analysis.
2. A data set resulting in a Weibull shape parameter (β) which was not close to unity for the operating period indicates a non constant mean life.

For the first case the MTTF was calculated using the lower 60% chi square confidence limit for failures occuring during the operating period:

$$MTTF = \frac{2T}{\chi^2_{(2r + 2),.6}} \tag{IV-20}$$

where T = Total time accumulated on both failed and surviving tubes

r = Number of failures

$\chi^2_{(2r + 2),.6}$ = The 60 percentile point of the chi square distribution with $2r + 2$ degrees of freedom.

For the second case the MTTF was calculated from the Weibull shape parameter and characteristic life for the operating period:

$$MTTF = \alpha\Gamma(1 + 1/\beta) \qquad \text{(IV-21)}$$

where Γ = The Gamma function

α = The Weibull characteristic life

β = The Weibull shape Parameter

V RELIABILITY MODELING

A. Introduction

The orientation of MIL-HDBK-217B toward reliability prediction of military equipment is to provide system designers data which will permit system reliability prediction. The data which will permit system reliability prediction includes the failure rate for components which comprise a planned system.

Because microwave tubes are components in many systems, it was desired that the reliability of microwave tubes be modeled to permit failure rate prediction.

Two basic types of models were developed. One type of model developed permits failure rate prediction and removal criterion prediction for specific individual tube types. The individual tube type models will enable predictions provided the tube to be used in a planned system has been modeled. The other type of model developed will enable failure rate and removal criterion predictions for general tube classes. The second model was required because the individual tube type models were not developed for all tubes due to a lack of data and because new tube types are likely to be introduced for planned systems.

B. Modeling of Individual Tube Type Reliability

1. Basic Model Structure

Investigation of tube failure mechanisms indicated, that all removal criteria are independent, meaning that the occurrence of a failure due to one cause does not influence the probability of occurrence of a failure for any other cause. Practically, this may be interperted as meaning that each failure may be attributed to one unique cause. The investigation into tube failure mechanisms resulted in the observation that a malfunction may occur in the tube or system which leads to a tube failure, but regardless of the cause of a failure the tube failed due to a single (independent) cause.

As a consequence of removal criteria independence, an assumption was made regarding the actual model. It was that the model is additive. In other words, the reliability of a tube is equal to the properly weighted sum of the tube reliability due to each removal criterion. Thus the basic structure of the model will be of the form,

$$R(t) = A_1R_1(t) + A_2R_2(t) + \ldots + A_nR_n(t)$$

where

$R(t)$ = Reliability of the tube at time t

= Probability the tube will not fail prior to time t

$R_i(t)$ = Probability the tube will not fail due to removal criterion i prior to time t

A_i = Weighting factor for failure mode i.

A second assumption was that the failure distributions are exponential. Therefore, the model may be expressed in terms of the failure rate for each failure mode. This removes the time dependence of the model as it assumes the failure rate to be constant over the time period of interest. The model describing failure rate is,

$$\lambda(t) = k_1\lambda_1(t) + k_2\lambda_2(t) + \ldots + k_n\lambda_n(t)$$

where

$\lambda(t)$ = Tube failure rate at time t. (Under the exponential assumption this is constant for all t)

$\lambda_i(t)$ = Failure rate for failure mode i at time t, (again constant for all t under the exponential assumption)

k_i = Weighting factor for failure mode i

2. Modifying Factors

There are several modifying factors which could modify the failure distributions for removal criteria for different tubes. The factors studied in the research were as follows:

a. Stress Factors

b. Location Factors

c. Shelf Life Factors

d. Importance Factors

e. Other Factors

a. Stress Factors

Discussions with tube experts during the course of the study and the previous experience of the project team indicated the possible existence of multiplicative factors which indicate the effect of a failure mode on tube reliability. The data on which this study was based did not conclusively indicate such a pattern. Had the pattern been apparent it would have meant that common failure mode distributions could be developed for classes of tubes. Individual differences resulting from stresses on the tubes could then be accounted for by the stress factors.

b. Location Factors

Some of the tubes studied were used in several different geographical areas. The data were analyzed to determine if significant differences in failure rates could be discerned due to such geographical location. No such consistent patterns were found in the data. It should be cautioned again, however, that all of the data studied in this analysis were for ground based installations, as these data were the only data containing such multiple location information.

c. Shelf Life Factors

Data were available to measure trends of shelf life effects on tube life. It was determined, however, that no such trends existed in the data. Discussions with the various tube manufacturers and users agree with the results from the data analysis. That is, if tubes are properly stored, their operating life should not be significantly reduced.

d. Importance Factors

These factors measure the importance of each removal criterion to the overall tube failure rate. They have been determined empirically by measuring the number of failures due to each removal criterion for each tube and dividing by the total number of failures for that tube being considered. They are therefore weighting factors which weight the removal criterion as to their importance to tube life.

e. Other Factors

Other considerations such as the effect of learning and environmental factors on individual tube reliability were made; however, each of the tubes for which data were collected generally were all used in the same environment or had little evidence of reliability change with time (learning effect). Therefore, none of the individual tube type models contain these factors. The tube class models, which will be introduced later, do contain these factors because appropriate combinations of individual tube type data allowed determination of these factors.

C. Modeling of Tube Classes

The individual tube type models discussed in Part "A" above are not sufficient for general reliability predictions of the type in MIL-HDBK-217B. For this reason two types of reliability models were developed based on the individual tube type reliability models. The first type may be used to predict the overall failure rate of a given microwave tube class (klystron, TWT, etc.) with a given set of operating parameters (power, frequency and duty cycle). The second type may be used to predict the failure rate and probability of occurrence of removal criterion for a given tube class (klystron, TWT, etc.) with a given set of operating parameters (power, frequency and duty cycle). The application of these two models to a particular tube results in a predicted base failure rate which must be modified by appropriate environmental and learning factors. These factors are published in MIL-HDBK-217B for microwave tubes. After extensive data analysis some of these factors have been modified and are listed herein.

1. Basic Model Structure

The overall failure rate model must provide a reliability prediction method based on tube operating parameters and appropriate modifying factors. The model structure for overall failure rate prediction for a given tube class is,

$$\lambda_p(P_j) = \Pi_L \Pi_E \lambda(P_j) \qquad \text{(V-1)}$$

where

$\lambda_p(P_j)$ = Predicted Overall Tube Failure Rate

Π_L = Learning Factor

Π_E = Environmental Factor

$\lambda_b(P_j)$ = Base Tube Failure Rate

P_j = Tube Parametric Classifications

$$j = 1, 2, \ldots m$$

λ_p and λ_b are both functions of tube parametric classifications.

The model structure for the removal criterion model for a given tube class is

$$\lambda_p(P_j) = \Pi_L \Pi_E \Pi_F(P_j)\ \lambda_b(P_j) \qquad (V-2)$$

where

$$\Pi_F(P_j) = \frac{\text{Base Failure Rate from Overall Failure Rate Model}}{\text{Base Failure Rate from Removal Criterion Model}}$$

$$\lambda_b(P_j) = k_1(P_j)\lambda_1(P_j) + k_2(P_j)\lambda_2(P_j) + \ldots + k_n(P_j)\lambda_n(P_j)$$

$k_i(P_j)$ = Importance factor of the ith removal criterion

$\lambda_i(P_j)$ = Failure rate of the ith removal criterion

Π_F, k_i and λ_i are all functions of tube parametric classifications.

2. Modifying Factors

a. Environmental Factors

Reliability data have been gathered for tubes in the following environments: ground fixed systems, ground mobile systems, sea-going systems, airborne external (pod) systems, and airborne internal systems. To be consistent with MIL-HDBK-217B the ground fixed systems were used as a baseline reliability standard. All environmental factors are expressed relative to the reliability of tubes in a ground fixed environment. The environmental factor (Π_E) is, therefore, a ratio of non-ground fixed failure rate to ground fixed failure rate for a given tube class and a given set of operating parameters. Reliability data on tubes in a ground based mobile/transportable environment and data on similar (or the same, in some cases) tubes in a ground fixed environment were compared. The ratio of failure rates after appropriate screening and interpretation of the data showed a consistently higher failure for tubes used in a ground mobile/transportable environment over tubes in the ground fixed installations.

Data were available on tube failures in airborne inhabited, airborne uninhabited, and sheltered sea-going systems. These data were compared with ground based-data and with each other to determine the naval sheltered environmental factor.

b. Learning Factors

The data gathered in some cases allowed analysis by year of manufacture. Engineering considerations lead to the hypothesis that as time progresses, procedures for operating a tube within a system change resulting in improved reliability. Furthermore, improved reliability was obtained through improvements in manufacturing techniques. The data analyzed by year of manufacture after proper screening supported this hypothesis. That is, tube reliability improved after several years of manufacturing experience.

3. Reliability Model

The data analyzed for each of the tube classes exhibited trends when failure rate was compared with tube parametric classifications and when failure rate was compared with environmental and learning considerations. The overall failure rate models and the removal criteria models, therefore, retained the structure hypothesized above. The models are presented in Section VI of this report.

VI. RESULTS OF DATA ANALYSIS AND MODELING

A. Introduction

As discussed in previous sections, the study has dealt with the reliability of individual tube types and the reliability of general tube classes. As will be described in this section, the analysis of individual tube type reliability resulted in individual tube type reliability models, individual tube type removal criteria models and individual tube type wearout times for those tubes with sufficient data. The analysis of these individual tube type models resulted in the development of general tube class overall reliability models and tube class removal criteria models for those tube classes with sufficient data. The effects of environment and learning have been modeled for all tubes.

B. Individual Tube Type Reliability Models

The failure rate for each of the tube types was determined from the cumulative hazard analysis or the chi square 60% upper confidence limit as discussed in the previous section. The reliability for the individual tube types studied is presented in Tables VI-1 through VI-8 as failure rate. An overall reliability function plot was made for each of the tube types modeled. The plots are in Appendix A. The reliability for a given time may be found by reading from the ordinate of the plot for the tube of interest the point corresponding to the desired time on the abscissa.

The probability of the tube not failing prior to a given time (reliability) taken from one of the reliability function plots may be used in determining the probability that the system will not fail prior to the given time. The system failure probabilities may be used in determining expected maintenance schedu[illegible] expected operational cost and other operational considerations.

TABLE VI-1 MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

CW KLYSTRONS

Tube No.	No. of Tubes	No. Failed	Avg. Power (KW)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
3KM300LA	28	20	100	400	64*
3K210000LQ	189	169	76	870	151
4KM170000LA	8	4	75	410	75*
VA853	36	36	75	900	222
8824	16	16	30	520	126
8825	9	9	30	630	121
8826	9	9	30	790	280
3KM50000PA1	108	88	23	330	116
3KM50000PA2	91	54	23	330	150*
3KM50000PA	305	282	20	330	111
4KM50LB	10	4	14	410	28*
4KM50LC	13	5	14	400	15*
4KM50SK	134	84	12	2600	37
4KM50SJ	13	8	12	2100	38*
4KM50000LR	592	423	12	870	57
4KM50000LQ	68	51	11	800	79
4K50000LQ	171	97	10	800	30*
3K50000LA	40	29	10	500	587
3K50000LF	13	8	10	620	54*
VA800E	10	5	10	2100	70*
VA856B	16	11	2	7600	65
4KM3000LR	203	79	2	800	138*

TABLE VI-1 (Continued)

CW KLYSTRONS (Cont'd)					
Tube No.	No. of Tubes	No. Failed	Avg. Power (KW)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
3K3000LQ	110	33	2	800	9*
3KM3000LA	100	60	2.3	490	19*
4K3CC	81	79	1.2	4700	605
VA888E	438	244	1	4700	233*
4K3SK	53	26	1	2600	29*

* Upper 60% chi square confidence limit
† Failure rate based on operation period

TABLE VI-2 MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

PULSED KLYSTRONS

Tube No.	No. of Tubes	No. Failed	Peak Power (MW)	Avg. Power (KW)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
4670	7	7	30	26	2900	39
8568	265	140	21	19	2900	234*
ZM3038A	447	426	15	30	2500	194
L3250	170	145	10	15	1300	69
Z5010A	163	152	10	15	1300	150
SAC42A	632	598	3	6	5600	102
X780D	23	21	2.5	75	1300	337
L3035	494	404	2.2	7	1300	66
VA842	143	120	1.3	75	400	18
L3403	515	437	1.3	75	400	93
4KMP10000LF	34	21	470 KW	4.6	600	43*

* Upper 60% chi square confidence limit
† Failure rate based on operation period

TABLE VI-3. MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

TRAVELING WAVE TUBES						
Tube No./ System	No. of Tubes	No. of Failures	Peak Pwr. (KW)	Avg. Pwr. (W)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
VTR5210A1	136	84	5	10	5600	145
ZM3167	484	443	5	10	5600	88
MA2001A	35	29	CW	250	560	165
VA138D	31	23	CW	70	420	53
WJ3751	16	4	CW	.001	2900	90*
§M5768	31	24				2203
§VA643	40	29				607
§ALQ94	158	158			HB	4530
§ALQ94	156	156			MB	4470
§ALQ94	65	65			LB	1865
§ALQ101	53	53			MB	4350
§ALQ101	36	36			LB	4350
§ALQ117	27	27				1100
§ALQ117	33	33			HB	910
§ALQ119	261	261			HB	1475
§ALQ119	131	131			MB	1185
§ALQ119	151	151			LB	1460

* Upper 60% chi square confidence limit
λ Failure rate based on operation period
§ Classified Power and Frequency

TABLE VI-4. MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

MAGNETRONS						
Tube No.	No. of Tubes	No. of Failures	Peak Pwr. (MW)	Avg. Pwr. (KW)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
QK338A	3200	3148	4.5	4.5	2800	463
6410A	10	1	4.5	4.5	2800	535**
7529	5	0	3.5	3.5	2800	353**
QK327A	455	433	3.5	2.5	2800	432
QK327A	6	1	3.5	2.5	2800	367**
SFD356	29	0	2.2	2.4	2870	125**
6517	3	0	1	1.3	1300	1267**
400615	74	53	1	1	1300	452
5586 F/M	131	88	800 KW	400 W	2800	559
5586 Fixed	31	23	800 KW	400 W	2800	499
5586 Mobile	90	69	800 KW	400 W	2800	669
8798 F/M	1391	1160	450 KW	450 W	2800	479
8798 Fixed	327	280	450 KW	450 W	2800	379
8798 Mobile	737	610	450 KW	450 W	2800	464
5780	10	0	250 KW	250 W	9000	80**
SFD352	118	5	230 KW	253 W	9000	263**

TABLE VI-4. (Continued)

MAGNETRONS (Cont'd)						
Tube No.	No. of Tubes	No. of Failures	Peak Pwr. (MW)	Avg. Pwr. (KW)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
6344	13	3	175 KW	149 W	5640	335**
SFD370	7	0	90 KW	99 W	9250	105**
SFD377A	3	0	90 KW	90 W	9375	200**
SFD342	28	0	75 KW	65 W	16500	55**
7452	10	0	70 KW	196 W	16000	263**
BLM198	8	0	70 KW	84 W	16250	213**
7256 F/M	1832	1554	40 KW	40 W	9100	533
7256	15	1	40 KW	40 W	9100	159**
7256 Fixed	706	619	40 KW	40 W	9100	520
7256 Mobile	855	714	40 KW	40 W	9100	554
2J55	5	0	40 KW	40 W	9375	366**

** Manufacturer's life test data - upper 60% chi square confidence limit
† Failure rate based on operation period unless data are manufacturer's life test results

TABLE VI-5 MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

TWYSTRONS						
Tube No.	No. of Tubes	No. of Failures	Peak Pwr. (MW)	Avg. Pwr. (KW)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
VA913A	135	123	5	10	5500	225
VA145H	17	13	5	10	3000	487
VA145E	42	28	3	5	3000	449
§VA144	40	30				847

† Failure rate based on operation period

§ Classified Power and Frequency

TABLE VI-6 MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

GRIDDED TUBES						
Tube No.	No. of Tubes	No. of Failures	Peak Pwr. (KW)	Avg. Pwr. (KW)	Freq. (MHz)	Failures/ 10^6 Hours † (λ)
7835	167	159	10 MW	60	450	136
2041	363	339	300	3	430	142
6952	424	414	224	4	430	390

† Failure rate based on operation period

TABLE VI-7. MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

AMPLITRON						
Tube No.	No. of Tubes	No. Failed	Peak Power	Avg. Power	Freq.	Failure/ 10^6 Hours † (λ)
§QK681	208	201				260

§ Classified Power and Frequency

TABLE VI-8 MICROWAVE TUBE CHARACTERISTICS AND FAILURE RATES

CROSSED FIELD AMPLIFIER						
Tube No.	No. of Tubes	No. Failed	Peak Power (KW)	Avg. Power (KW)	Freq.	Failure/ 10^6 Hours † (λ)
SFD261	52	10	125	1	S	209*
SFD261	10	5	125	1	S	127**

* Upper 60% chi square confidence limit

** Manufacturer's life test data - upper 60% chi square confidence limit

† Failure rate based on operation period unless data are manufacturer's life test results

Because reliability models have not been developed for all tubes due to a lack of sufficent data, an appropriate engineering judgement will be necessary to obtain a failure rate prediction for a tube which has not been modeled. The engineer may consider reliability models for tubes with characteristics similar to the tube of interest as a basis for a judgement leading to the desired reliability prediction. Other models have been developed based on the individual tube type reliability models which predict the reliability of tube classes (klystrons, TWT's, etc.) based on tube parametric classifications. These tube class reliability models may be used where no model is available for a specific tube of interest.

C. Individual Tube Type Removal Criteria Models

The failure rates and frequency of occurrence for each of the removal criteria for each tube studied are summarized in Tables VI-9 through VI-23. The product of the frequency of occurrence and failure rate for each removal criterion is a measure of the relative contribution of each removal criterion to the overall failure rate of the tube.

The relative contribution to a tube's failure rate by the various removal criteria may be used as a guide to direct corrective actions for the purpose of reliability improvement. The reduction of the failure rate for the removal criterion having the largest contribution will reduce the failure rate of the tube, therefore, reducing the expenditures necessary to replace failed tubes. Removal criteria having a significant secondary and tertiary contribution to the overall failure rate should also be considered in a reliability improvement research program. Research to reduce the failure rate for any removal criterion should not necessarily concentrate on improving only the tube. The system or at least the tube-system interface, in many cases is the cause of tube failures.

TABLE VI-9

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

CW KLYSTRON

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
VA853			343				
VA888E	414	233	805		358		
3KM3000LA		38					
3KM50000PA	113	76	165			98	
3KM50000PA1	153		157				
3KM50000PA2	110		302			375	
3K210000LQ		38	243			121	
3K3000LQ		21	56				
3K50000LA		837					
4KM3000LR		30	71				
4KM50SK		49	83				
4KM50000LQ							
4KM50000LR F/M	78	49	80		139	110	
4KM50000LR Mobile			233				
4KM50000LR Fixed	53	51	73				
4K3CC	688	418	2738		1217		
4K3SK		49					
4K50000LQ	39	35	52				

TABLE VI-10

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

CW KLYSTRON

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
VA853							
VA888E				344			
3KM3000LA							
3KM50000PA				79			222
3KM50000PA1				327			
3KM50000PA2				155			
3K210000LQ				363		218	199
3K3000LQ							
3K50000LA							
4KM3000LR							
4KM50SK				69		127	63
4KM5000LQ				108		108	92
4KM50000LR F/M			119	108		131	74
4KM50000LR Mobile						178	166
4KM50000LR Fixed			90	128		138	63
4K3CC				521			
4K3SK							
4K50000LQ				102		71	60

TABLE VI-11

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

PULSED KLYSTRON

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
L3035	98	49	112		93	92	[illegible]
L3250		53	136				100
L3403		117	135			205	1055
SAC42A	97	93	124	121		183	128
VA842		24	77				
X780D			358				
ZM3038A	688	202	308		301		
Z5010A		107	227			281	175
4KMP10000LF			160				
8568			130				

TWT

Tube Number	Filament	Emission	Gassy
ZM3167	139	88	165
MA2001A	110	201	899
VTR5210A1	143	207	
VA138D	141	55	

TABLE VI-12

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

PULSED KLYSTRON

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
L3035	86		102	86		93	65
L3250	116		80	124			45
L3403				139	129		
SAC42A	123			108		104	192
VA842				47			41
X780D							
ZM3038A	326		314	349			289
Z5010A	637			258			258
4KMP10000LF							
8568		104	120	62			

TWT

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
ZM3167				146		112	
MA2001A				325			
VTR5210A1				169			
VA138D							

TABLE VI-13

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

MAGNETRONS

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
QK327A	426	302	766				
QK338A	368	237	846				
400615							
5586 F/M		615	1844				
5586 Fixed		631	1025				
5586 Mobile		732	1469				
7256 F/M	650	447	690		790		
7256 Fixed	844	416	649		622		
7256 Mobile	575	490	733		916		
8798 F/M	753	319	730		693		
8798 Fixed	1357	245	650				
8798 Mobile	639	362	720		760		

TWYSTRON

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
VA913A		249	389		366		

TABLE VI-14

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

MAGNETRONS

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
QK327A	718			419		596	592
QK338A	635		562	435		614	640
400615				546		865	
5586 F/M				735			
5586 Fixed				490			
5586 Mobile				722			
7256 F/M	659		565	629		562	742
7256 Fixed	780		518	669		608	1124
7256 Mobile	591		632	658		511	651
8798 F/M	532		782	667		923	940
8798 Fixed				571			
8798 Mobile	632			738		786	

TWYSTRON

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
VA913A	276						199

TABLE VI-15

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

GRIDDED TUBE

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
7835		94	215				
6952		354	778				
2041	162	116					
AMPLITRON							
QK681		120	363				

TABLE VI-16

MICROWAVE TUBE REMOVAL CRITERIA FAILURE RATES

GRIDDED TUBE

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
7835				209		202	223
6952				672		365	644
2041				221			234
AMPLITRON							
QK681	271			398			178

TABLE VI-17

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

CW KLYSTRON

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
VA853		.08	.61			.03	.06
VA800E		.40				.20	
VA856B	.27		.18				
VA888E	.24	.08	.14		.08	.04	
3KM300LA		.05	.40	.05			
3KM3000LA	.02	.62	.12		.02	.02	
3KM50000PA	.44	.10	.20	.02	.02	.03	.01
3KM50000PA1	.29	.06	.18			.05	
3KM50000PA2	.20	.02	.24			.19	
3K210000LQ	.04	.04	.32	.04	.02	.07	
3K3000LQ		.55	.33			.03	
3K50000LA	.07	.38	.10	.03	.07	.03	
3K50000LF	.13	.38	.13			.13	
4KM170000LA		.25	.25				

TABLE VI-17 (Continued)

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
4KM3000LR	.01	.63	.18			.01	
4KM50LB	.25		.25				
4KM50LC	.20		.20			.20	
4KM50SJ		.13			.13		
4KM50SK	.05	.15	.11		.02	.02	
4KM50000LQ	.08	.02	.12	.02		.06	
4KM50000LR F/M	.04	.07	.17		.02	.04	
4KM50000LR Mobile	.07	.04	.11		.01	.03	
4KM50000LR Fixed	.03	.09	.20		.03	.03	
4K3CC	.32	.14	.10	.01	.09	.01	
4K3SK	.15	.31	.27		.08		
4K50000LQ	.37	.08	.15		.01	.02	

TABLE VI-18

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

CW KLYSTRON

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
VA853				.06			.08
VA800E				.20			
VA856B				.18			.27
VA888E				.17	.03	.02	.02
3KM300LA			.10	.20			
3KM3000LA				.07			.05
3KM50000PA				.06	.02	.01	.03
3KM50000PA1			.01	.16	.01	.02	.03
3KM50000PA2			.06	.20		.04	.02
3K210000LQ			.02	.13		.12	.15
3K3000LQ				.09			
3K5000LA				.17		.07	
3K5000LF							.25
4KM170000LA				.25			.25

TABLE VI-18 (Continued)

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
4KM3000LR			.01	.06		.04	.03
4KM50LB							.50
4KM50LC				.20			.20
4KM50SJ				.13			.63
4KM50SK			.05	.19		.08	.27
4KM50000LQ				.18		.27	.24
4KM50000LR F/M			.07	.07		.13	.35
4KM50000LR Mobile			.09	.06		.20	.36
4KM50000LR Fixed			.08	.07		.13	.32
4K3CC	.01		.05	.19			.04
4K3SK				.12		.04	
4L50000LQ				.07		.07	.15

TABLE VI-19

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

PULSED KLYSTRON

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
L3035	.06	.13	.08		.21	.05	.03
L3250	.01	.12	.12	.01	.07	.01	.12
L3403	.02	.08	.48		.01	.02	.03
SAC42A	.04	.32	.10	.13		.04	.03
VA842	.02	.14	.42			.01	
X780D	.05	.05	.71				
ZM3038A	.04	.19	.39		.06	.01	.02
Z5010A	.01	.13	.39		.01	.07	.06
4KMP10000LF	.05	.19	.57				
8568		.03	.13				

TWT

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
ZM3167	.04	.70	.05				
WJ3751		.50	.50				
MA2001A	.24	.24	.31				
VTR5210A1	.05	.75	.06				
VA138D	.26	.43					
VA643		.14	.38				

TABLE VI-20

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

PULSED KLYSTRON

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
L3035	.08		.07	.08		.09	.06
L3250	.11		.07	.26		.02	.06
L3403	.01			.25	.05	.01	.02
SAC42A	.12		.01	.13		.02	.04
VA842	.02		.02	.20	.02	.05	.07
X780D			.05				.14
ZM3038A	.14		.02	.08		.01	.02
Z5010A	.05		.01	.07	.04		.15
4KMP10000LF				.14	.05		
8568		.10	.50	.17			

TWT

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
ZM3167	.01			.16		.02	
WJ3751							
MA2001A				.10			
VTR5210A1				.05		.04	
VA138D				.09			
VA643	.15		.02	.15		.02	.05

TABLE VI-21

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

MAGNETRON

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
QK327A	.39	.11	.07		.01		
QK338A	.29	.06	.20				
400615	.04	.06	.15	.02			
5586 F/M	.05	.23	.30	.01	.07		
5586 Fixed		.30	.30				
5586 Mobile	.04	.22	.26		.09		
7256 F/M	.06	.24	.42		.04		
7256 Fixed	.05	.27	.45		.03		
7256 Mobile	.06	.22	.41		.05		
8798 F/M	.05	.19	.32		.05		
8798 Mobile	.06	.21	.37		.05		
8798 Fixed	.05	.22	.23		.02		

TWYSTRON

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
VA913A	.01	.20	.30		.05	.11	.02
VA145H	.08	.15	.31				.15
VA145E	.07	.04	.36			.04	.04
VA144		.13	.23	.16			.06

TABLE VI-22

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

MAGNETRON

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
QK327A	.05		.01	.23		.04	.06
QK338A	.09		.06	.16		.09	.02
400615	.13		.09	.21		.21	.06
5586 F/M	.01		.05	.25		.01	
5586 Fixed				.30			
5586 Mobile	.01		.04	.30			
7256 F/M	.03		.01	.13		.02	.03
7256 Fixed	.03		.01	.09		.02	.03
7256 Mobile	.04		.01	.15		.02	.02
8798 F/M	.01		.02	.28		.04	.01
8798 Mobile	.01		.01	.22		.04	.01
8798 Fixed	.02		.03	.39		.02	.01

TWYSTRON

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
VA913A	.14		.02	.05	.02	.01	.07
VA145H	.15				.15		
VA145E	.07		.11	.11	.04	.07	
VA144				.10	.06		.03

TABLE VI-23

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

GRIDDED TUBE

Tube Number	Filament	Emission	Gassy	Window	Mechanical	Focusing	Coolant Leak
7835	.03	.11	.14				.02
6952	.01	.50	.02				.01
2041	.02	.18	.02		.01		
AMPLITRON							
QK681		.14	.38				

TABLE VI-24

MICROWAVE TUBE REMOVAL CRITERIA IMPORTANCE FACTORS

GRIDDED TUBE

Tube Number	Oil System	Heater Seal	Window Arcing	Arcing/ Short	Magnetic System	Waveguide System	Cooling System
7835			.03	.51	.01	.06	.07
6952				.3[illegible]		.02	.03
2041				.65		.01	.05
AMPLITRON							
QK681	.15		.02	.15		.02	.05

D. Individual Tube Type Wearout Times

The cumulative Weibull hazard plots were inspected to determine appropriate wearout region for each tube analyzed. A steep decrease of slope on the cumulative hazard plot indicates the wearout point. Tables VI-25 through VI-30 summarize the results of the wearout analysis. The wearout region of tube life is that period when the failure rate begins to increase as the radiant time increases. Depending on considerations of tube cost and maintenance cost for a particular system, it may be desirable to remove an operating tube when it reaches the beginning of the wearout period listed. This is a preventative maintenance practice because the probability of a tube failing begins to increase more rapidly for a tube in the wearout region of the life cycle than for a tube in the operating period.

E. Modifying Factors

In order that the reliability models developed during the study be consistent with MIL-HDBK-217B, they are based on the reliability of tubes in fixed ground based installations and on the reliability of tubes which have been in use for several years. To predict the reliability of a tube not in the above two categories, modifying factors describing the effects of environment and learning must be applied to the model.

1. Environmental Factors

a. Ground Fixed

Over half of the tubes in the McClellan data were operated in a ground fixed environment. Tubes used in ground fixed systems generally have a lower failure rate than tubes in other environments because there is less vibration and more protective equipment in the ground fixed systems. Since it is the reference environment, the ground fixed factor is arbitrarily given the value of one.

TABLE VI-25. BEGINNING OF WEAROUT PERIOD FOR MICROWAVE TUBE LIFE CYCLES

CW KLYSTRONS		
Tube No.	Weibull Shape Parameter (β)	Beginning of Wearout Period (Hours)
4KM50LB	.61	1100*
3K50000LF	1.42	2000*
4KM50SJ	.99	2100*
VA800E	1.07	3000*
3K50000LA	.94	3500
8826	.65	5000*
4K3CC	.78	5000
4K3SK	1.32	6500*
8825	.72	9000*
3KM300LA	.64	10000
8824	.82	10000*
VA853	.85	10000
3KM50000PA2	.75	16000
3K3000LQ	.64	9000
4KM3000LR	.61	13500
VA888E	.92	20000*
VA856B	.81	22000*
4KM50000LQ	1.21	20000
4K50000LQ	1.14	34000*
3KM50000PA1	.75	40000*

TABLE VI-25 (Continued)

CW KLYSTRONS (Cont'd)

Tube No.	Weibull Shape Parameter (β)	Beginning of Wearout Period (Hours)
4KM50LC	1.9	40000*
4KM50SK	1.07	46000*
4KM170000LA	3.79	50000*
3KM50000PA	.81	57000*
3K210000LQ	.69	71000*
4KM50000LR	.88	80000*
3KM30000LA	.75	100000*

*No wearout observed; maximum failure time recorded.

TABLE VI-26. BEGINNING OF WEAROUT PERIOD FOR MICROWAVE TUBE LIFE CYCLES

PULSED KLYSTRONS		
Tube No.	Weibull Shape Parameter (β)	Beginning of Wearout Period (Hours)
ZM3038A	.75	7500
4670	.50	10000
8568	.55	10700
VA842	.54	13000
Z5010A	.78	13000
X780D	.59	18000*
L3403	.83	20000
4KMP10000LF	.78	30000
SAC42A	.80	80000*
L3250	.64	90000*
L3035	.88	90000*

*No wearout observed; maximum failure time recorded.

TABLE VI-27. BEGINNING OF WEAROUT PERIOD FOR MICROWAVE TUBE LIFE CYCLES

TRAVELING WAVE TUBES		
Tube No.	Weibull Shape Parameter (β)	Beginning of Wearout Period (Hours)
M5768	1.23	750
WJ3751	1.07	2300*
VA643	.63	3000
VA138D	1.01	4200*
MA2001A	.71	10000
ZM3167	1.04	60000*
VTR5210A1	1.28	21000*

*No wearout observed; maximum failure time recorded.

TABLE VI-28. BEGINNING OF WEAROUT PERIOD FOR MICROWAVE TUBE LIFE CYCLES

MAGNETRONS		
Tube No.	Weibull Shape Parameter (β)	Beginning of Wearout Period (Hours)
7256 Fixed	1.45	4900
7256 Mobile	1.44	5200
8798 Mobile	1.14	6000
5586 Fixed	.99	8000*
5586 Mobile	.87	8000*
5586 F/M	.83	9000*
7256 F/M	1.45	10000*
8798 Fixed	1.15	9500
400615	.92	11000*
QK327A	1.04	19000*
8798 F/M	1.11	25000*
QK338A	.88	35000*

*No wearout observed; maximum failure time recorded.

TABLE VI-29. BEGINNING OF WEAROUT PERIOD FOR MICROWAVE TUBE LIFE CYCLES

TWYSTRONS		
Tube No.	Weibull Shape Parameter (β)	Beginning of Wearout Period (Hours)
VA144	.66	4100*
VA145E	.73	6000*
VA145H	.67	9000*
VA913A	.90	11000

*No wearout observed; maximum failure time recorded.

TABLE VI-30 BEGINNING OF WEAROUT PERIOD FOR MICROWAVE TUBE LIFE CYCLES

GRIDDED TUBES		
Tube No.	Weibull Shape Parameter (β)	Beginning of Wearout Period (Hours)
6952	1.12	7000
2041	.87	13000
7835	.93	15000

b. Ground Mobile

Tubes in ground mobile systems are subjected to more vibration and have less protective equipment than those in a fixed environment. Several tube types in the data were used both in fixed and mobile environments. By comparing the reliability of tubes in a mobile environment with tubes having similar operating parameters used in a fixed environment and tubes used in both environments, the ground mobile factor was found to be 3.

c. Airborne Inhabited

Airborne inhabited environment refers to tubes operated in the aircraft as opposed to a pod. This environment subjects a tube to more, and usually higher frequency vibration than a mobile or fixed ground based environment. There are more abrupt jolts due to landings and air maneuvers. Appropriate comparison of the failure rate of tubes in an airborne inhabited environment with the failure rate of tubes in other environments resulted in modifying factors of 6.5.

d. Airborne Uninhabited

The airborne uninhabited environment refers primarily to systems located in wing pods. These units are subjected to even greater vibrations and jolts as the wings vibrate more than the fuselage. Appropriate comparison of the reliability of the pod tubes with the reliability of tubes in other environments resulted in a modifying factor of 8.

e. Naval Sheltered

The naval sheltered environment refers to seagoing systems which are protected from the weather. These tubes suffer a higher failure rate than ground based systems due to the corrosive effects of the salt laden air, vibration, and less protective equipment than the ground based systems. The reliability of naval sheltered tubes appropriately compared to the reliability of tubes in other environments resulted in a naval sheltered environmental factor of 6.5.

Table VI-31 summarizes the environmental modifying factors.

2. Learning Factor

The learning factor refers to the improvement in failure rate due to learning in the production, operation, and maintenance processes. For tubes being built and used for the first time, there may be production and operation problems which can result in a high failure rate. With time the problems are solved, and workers gain expertise in constructing and operating the tubes. As a result, the failure rate decreases as more tubes are built and used. Some of the tubes in the data base were in the one to three-year age category. Comparing the failure rate of these tubes with the failure rate of tubes with similar operating parameters which have been in production many years resulted in a learning factor of 3. Tubes which have been in production for over three years did not display noticeable differences in failure rate from the older tubes. There were no tubes which had been in production less than a year in the data base. The learning factor of 10 for this age category was adopted from the MIL-HDBK-217B. Table VI-32 summarizes the learning factors to be used when predicting tube reliability with the models presented in this section.

F. Overall Failure Rate Models

Failure rates for the following classes of tube have been modeled as a function of tube operating parameters and are consistent with MIL-HDBK-217B notation:

1. Klystrons
2. Magnetrons
3. Traveling Wave Tubes
4. Twystrons
5. Gridded Tubes (Tetrodes and Triodes)

TABLE VI-31. ENVIRONMENTAL MODIFYING FACTORS

ENVIRONMENT	FACTOR (π_E)
GROUND FIXED (G_F)	1.0
GROUND MOBILE (G_M)	3.0
AIRBORNE INHABITED (A_I)	6.5
AIRBORNE UNINHABITED (A_U)	8.0
NAVAL SHELTERED (N_S)	6.5

TABLE VI-32 LEARNING FACTORS

PERIOD	π_L
Less than 1 year	10.0
1 - 3 years	3.0
More than 3 years	1.0

Recall from section V, the basic model structure for the overall failure rate model is

$$\lambda_p = \lambda_b \pi_E \pi_L \text{ failures per } 10^6 \text{ hr.} \quad \text{(VI-1)}$$

where λ_p = part failure rate

= function of tube operating parameters

λ_b = base failure rate

= function of tube operating parameters

π_E = environmental factor

π_L = learning factor

A procedure for use of the model in estimating failure rates is as follows:

Step 1: Identify the tube parameters indicated in Table VI-33 for the appropriate tube class.

Step 2. Compute the following parameters of the tube:

a. For CW klystrons, multiply average power in KW by frequency in GHz to obtain a parameter with units of KW-GHz.

b. For pulsed klystrons, multiply peak power in MW by frequency in GHz to obtain a MW-GHz parameter.

c. For pulsed magnetrons, multiply peak power in MW by frequency in GHz to obtain a MW-GHz parameter.

d. For CW TWT's, multiply average power in W by frequency in GHz to obtain a W-GHz parameter.

e. For pulsed TWT's, multiply peak power in KW by frequency in GHz to obtain a KW-GHz parameter.

f. For pulsed Twystrons, multiply peak power in MW by frequency in GHz to obtain a parameter with units of MW-GHz.

TABLE VI-33. TUBE PARAMETERS REQUIRED
OVERALL FAILURE RATE MODEL

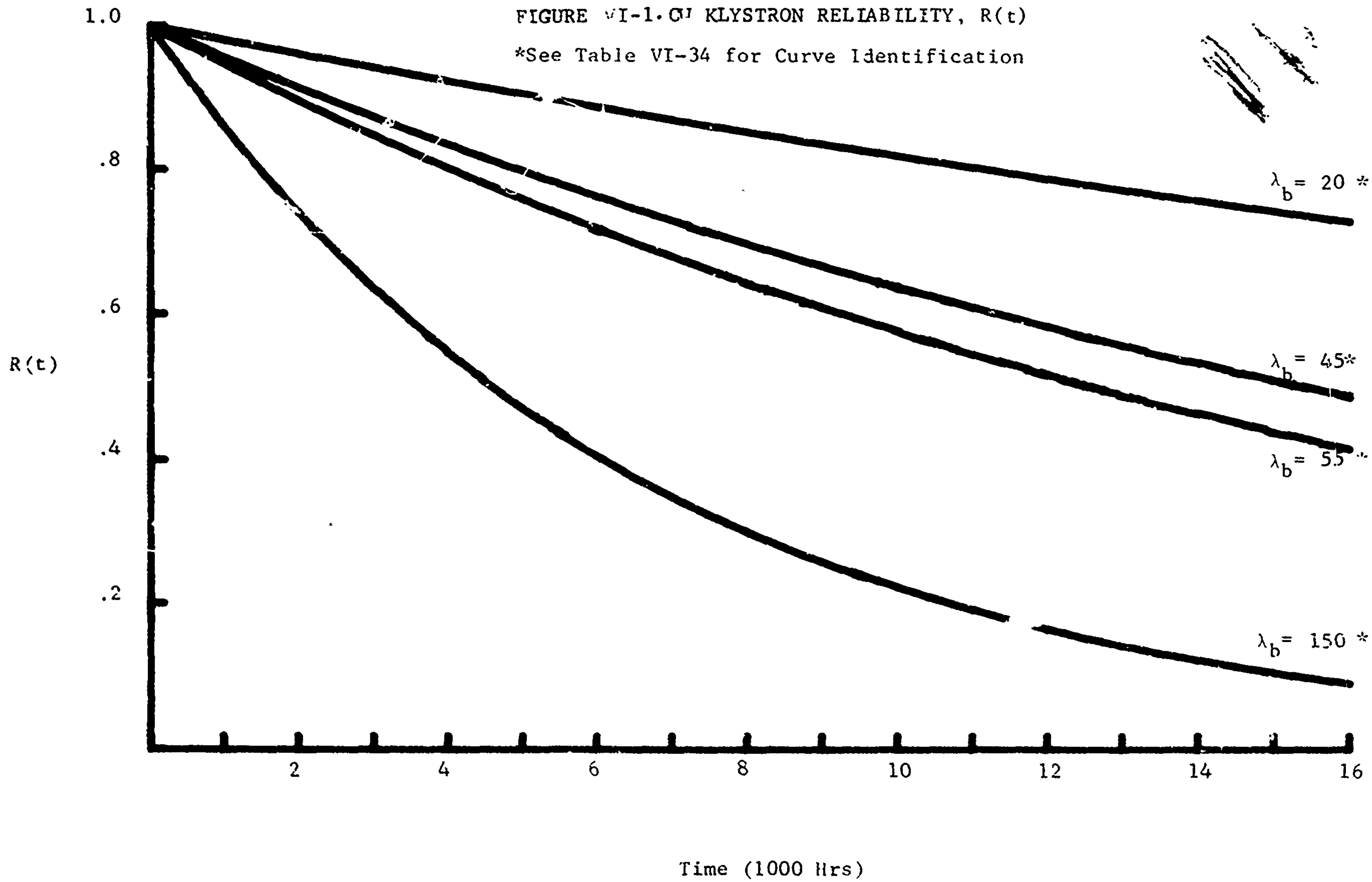
TYPE TUBE	PARAMETERS NEEDED
CW Klystrons	Average power, frequency
Pulsed Klystrons	Peak power, frequency
Pulsed Magnetrons	Peak power, duty cycle, frequency
Pulsed TWT's	Peak power, frequency
CW TWT's	Average power, frequency
Gridded Tubes	Duty cycle
Twystrons	Peak power, frequency

TABLE VI-34. CW KLYSTRON BASE FAILURE RATES

POWER X FREQUENCY (KW) x (GHz)	FAILURES PER 10^6 HOURS (λ_b)
Below 7	20
7-10	45
10-35	55
Above 35	150

FIGURE VI-1. CW KLYSTRON RELIABILITY, R(t)

*See Table VI-34 for Curve Identification



Step 3. Enter the appropriate table (Table VI-34 through VI-40) to determine the base failure rate (λ_b).

Step 4. Enter Table VI-31 to determine the environmental factor, Π_E.

Step 5. Enter Table VI-32 to determine the learning factor, Π_L.

Step 6. Compute the predicted part failure rate as the product of the base failure rate, the environmental factor, and the learning factor, i.e., $\lambda_p = \lambda_b \pi_E \pi_L$ failures per million hours.

G. Removal Criteria Models

Failure rates and importance factors for removal criteria for the following classes of tubes have been modeled as a function of tube operating parameters and are consistent with MIL-HDBK-217B notation. The classes of tubes are

1. Klystrons
2. Magnetrons
3. Traveling Wave Tubes
4. Twystrons
5. Gridded Tubes (Tetrodes and Triodes)

Recall from section V, the basic model structure for the tube class removal criteria model is

$$\lambda_b = k_1\lambda_1 + k_2\lambda_2 + \ldots + k_n\lambda_n \qquad \text{(VI-2)}$$

$$\lambda_p = \lambda_b \pi_E \pi_L \qquad \text{(VI-3)}$$

where λ_b = base failure rate

k_i = weighting factor for removal criterion i

λ_i = failure rate for removal criterion

λ_p = part failure rate

π_E = environmental modifying factors

π_L = learning factors

TABLE VI-35. PULSED KLYSTRONS BASE FAILURE RATES

PEAK POWER X FREQUENCY (MW) X (GHz)	FAILURES PER 10^6 HOURS (λ_b)
Below 10	80
10-25	120
25-35	180
Above 35	240

TITLE VI-36. PULSED MAGNETRONS BASE FAILURE RATES

PEAK POWER X FREQUENCY (MW) X (GHZ)	FAILURES PER 10^6 HOURS (λ_b) DUTY CYCLE Below 0.001	Above 0.001
Below 5	410	440
5-10	430	460
Above 10	450	470

[redacted]

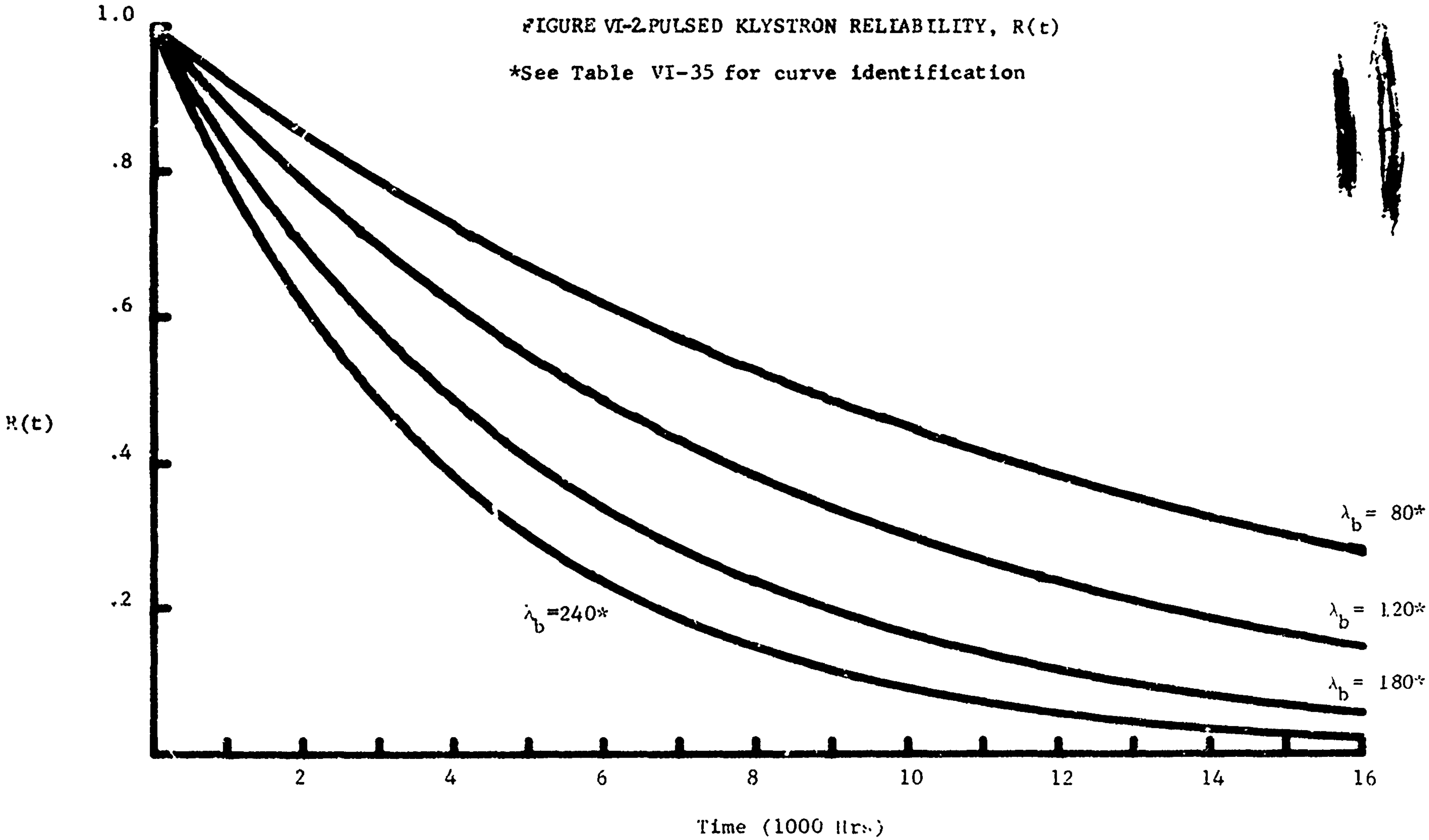


FIGURE VI-2 PULSED KLYSTRON RELIABILITY, R(t)

*See Table VI-35 for curve identification

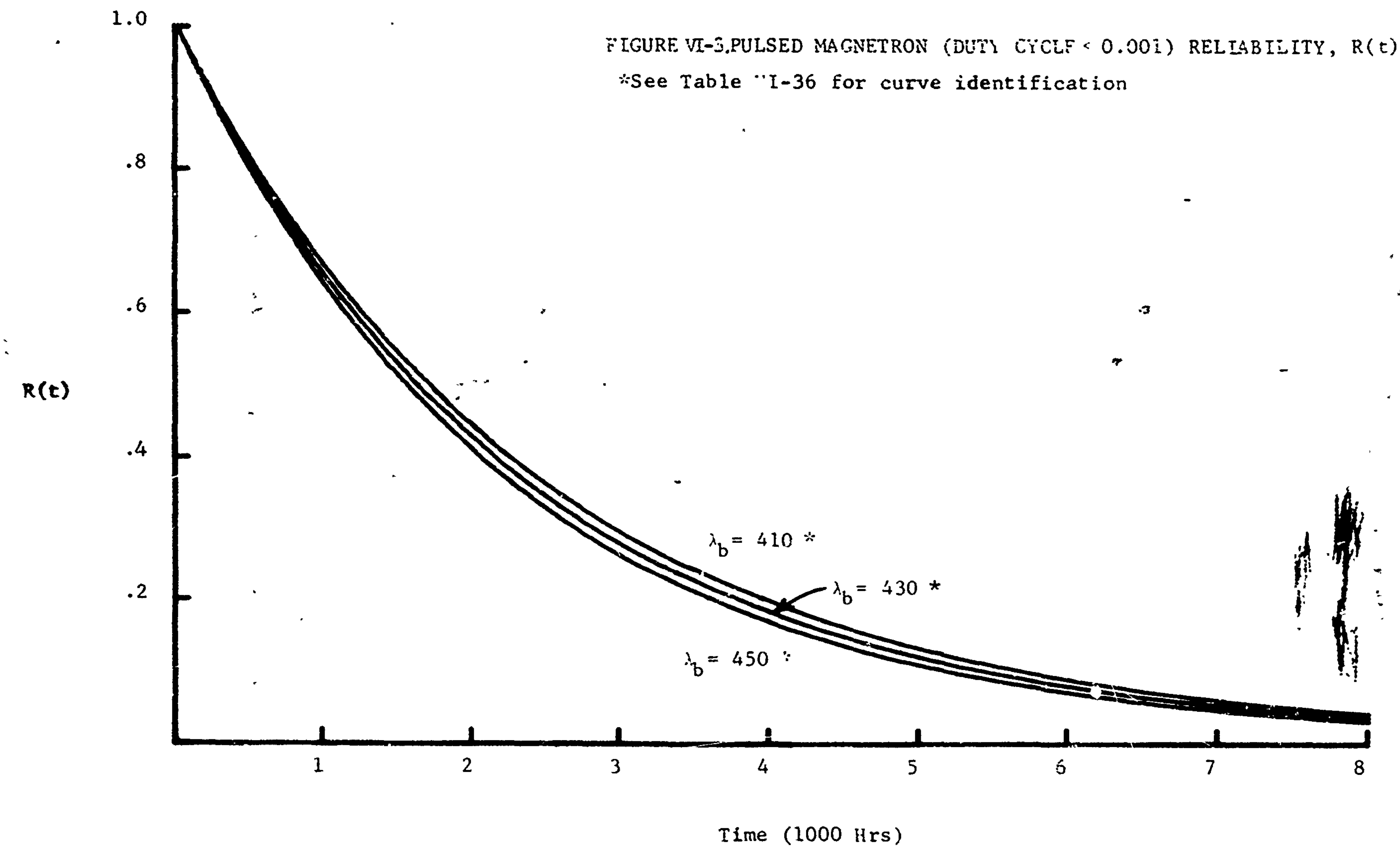


FIGURE VI-3. PULSED MAGNETRON (DUTY CYCLE < 0.001) RELIABILITY, R(t)

*See Table VI-36 for curve identification

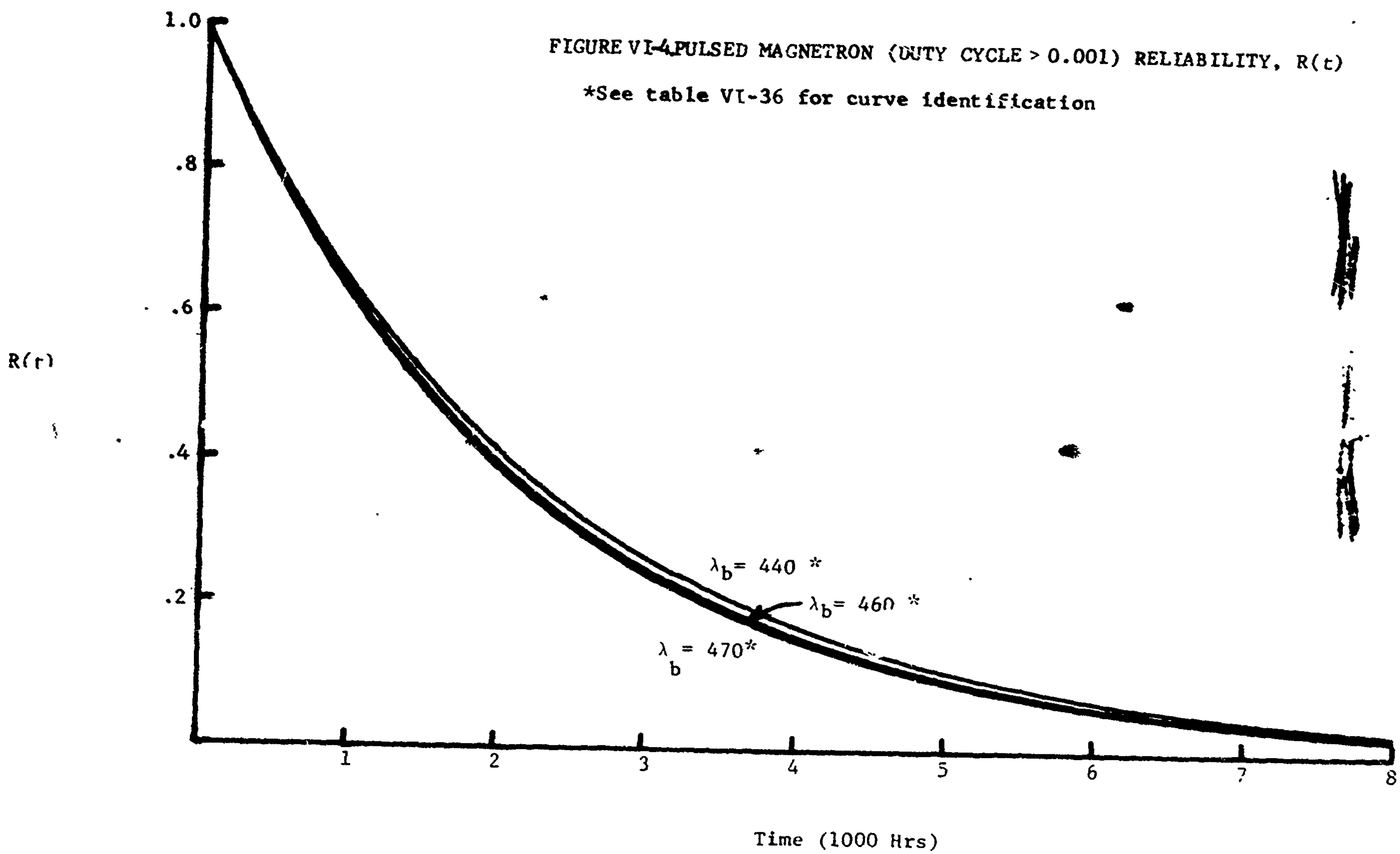


FIGURE VI-4 PULSED MAGNETRON (DUTY CYCLE > 0.001) RELIABILITY, R(t)

*See table VI-36 for curve identification

TABLE VI-37. CW TWT'S BASE FAILURE RATES

AVERAGE POWER X FREQUENCY (W) X (GHz)	FAILURES PER 10^6 HOURS (λ_b)
Below 100	60
100-500	300
500-1000	450
Above 1000	550

TITLE VI-38. PULSED TWT'S BASE FAILURE RATES

PEAK POWER X FREQUENCY (KW) X (GHz)	FAILURES PER 10^6 HOURS (λ_b)
Below 100	110
100-200	180
200-300	220
Above 300	260

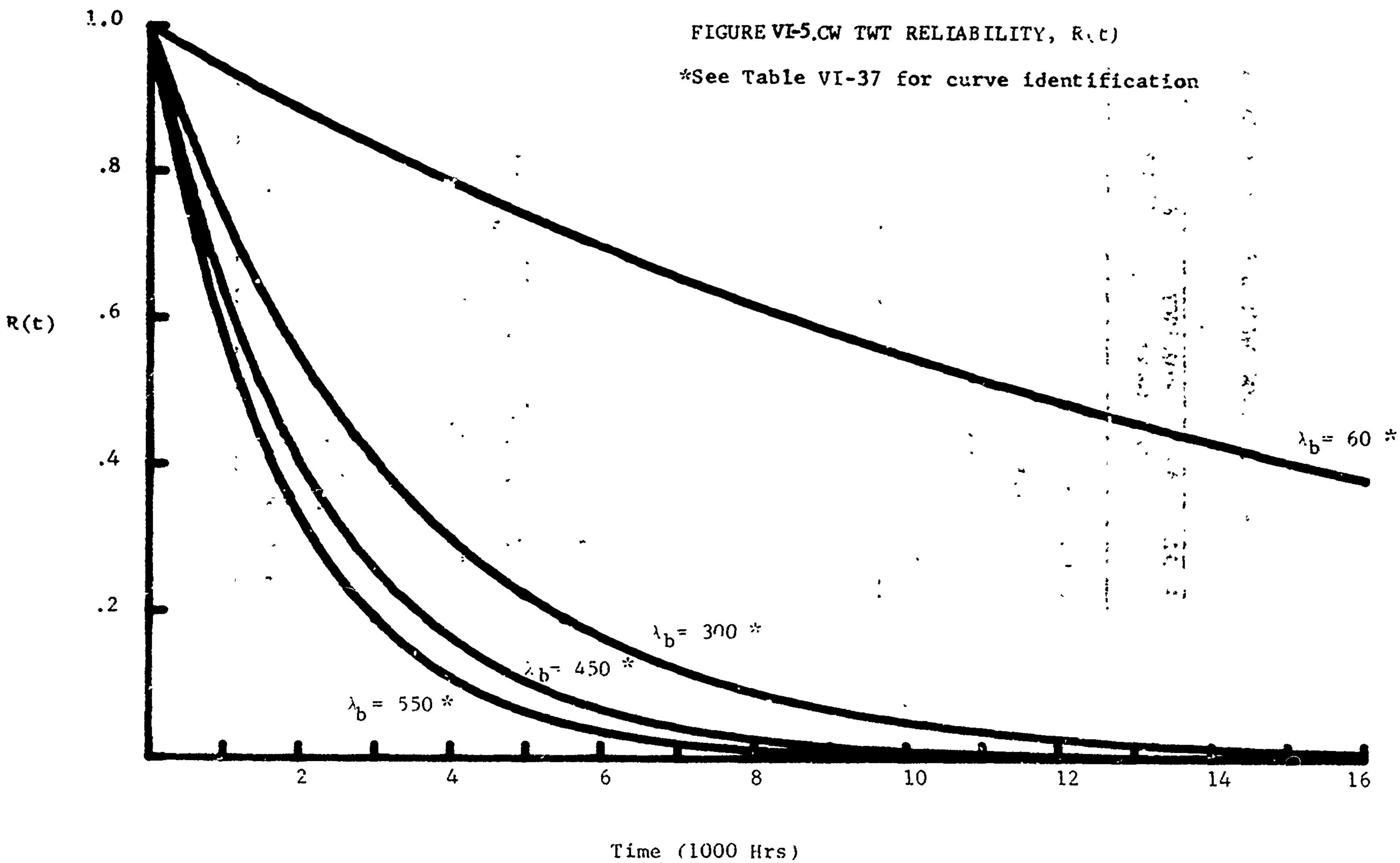


FIGURE VI-5 CW TWT RELIABILITY, R(t)

*See Table VI-37 for curve identification

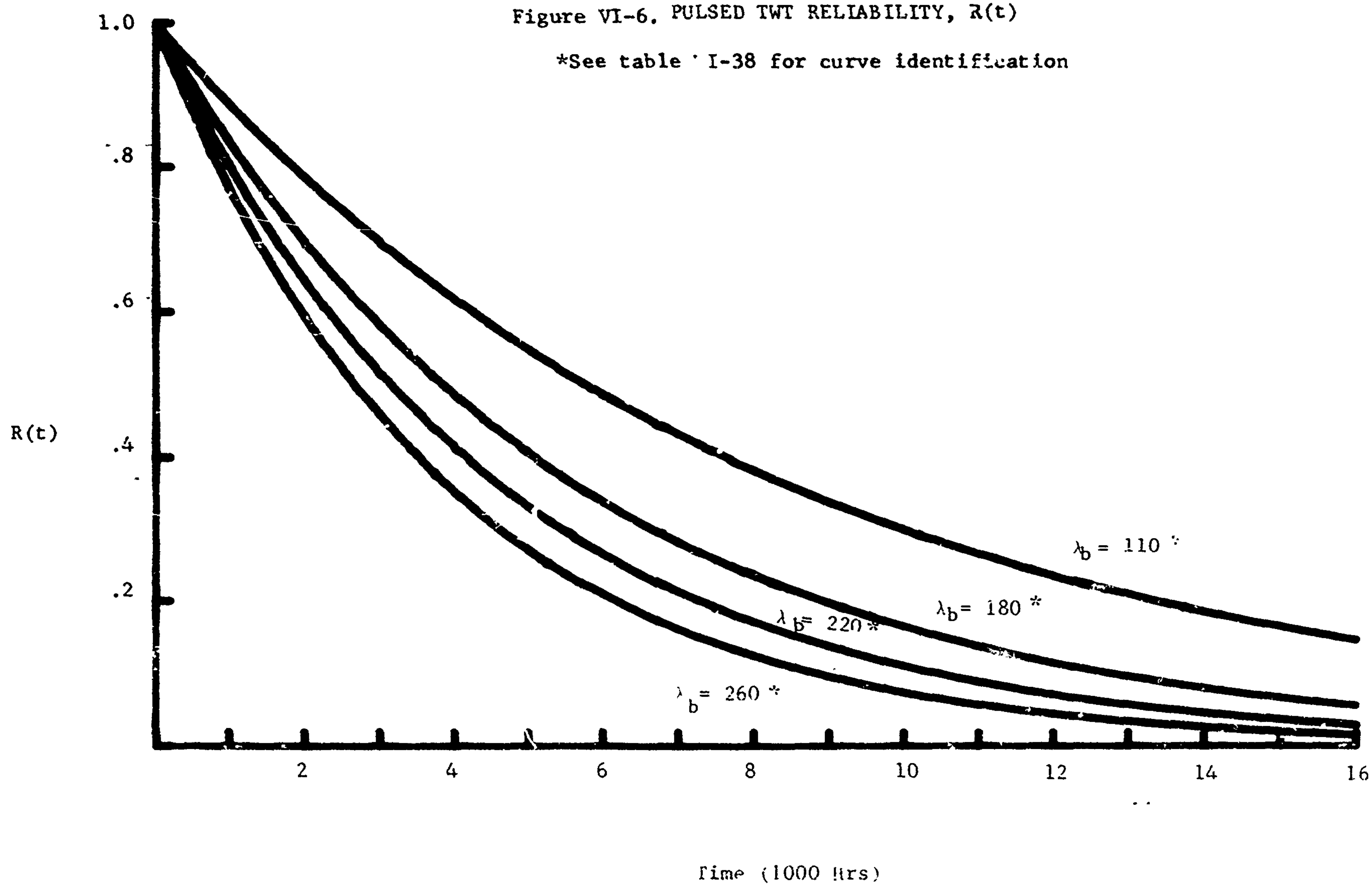


Figure VI-6. PULSED TWT RELIABILITY, R(t)

*See table VI-38 for curve identification

TABLE VI-39. PULSED GRIDDED TUBES BASE FAILURE RATES

DUTY CYCLE	FAILURES PER 10^6 HOURS (λ_b)
Below 0.0075	175
0.0075-0.0150	200
0.0150-0.0220	400

TABLE VI-40. PULSED KLYSTRONS BASE FAILURE RATES

PEAK POWER X FREQUENCY (MW) X (GHz)	FAILURES PER 10^6 HOURS (λ_b)
Below 10	150
10-20	175
20-30	275
Above 30	300

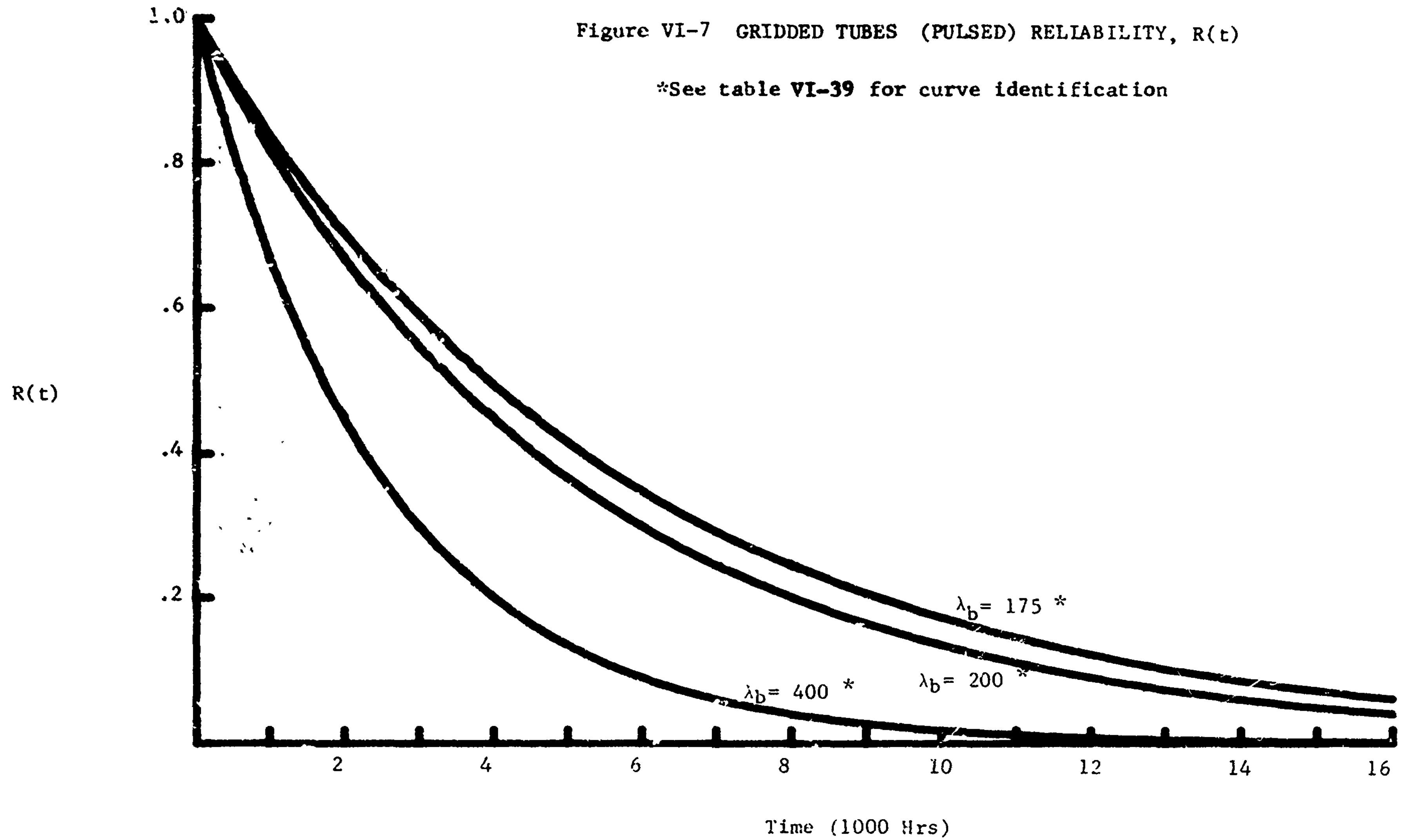
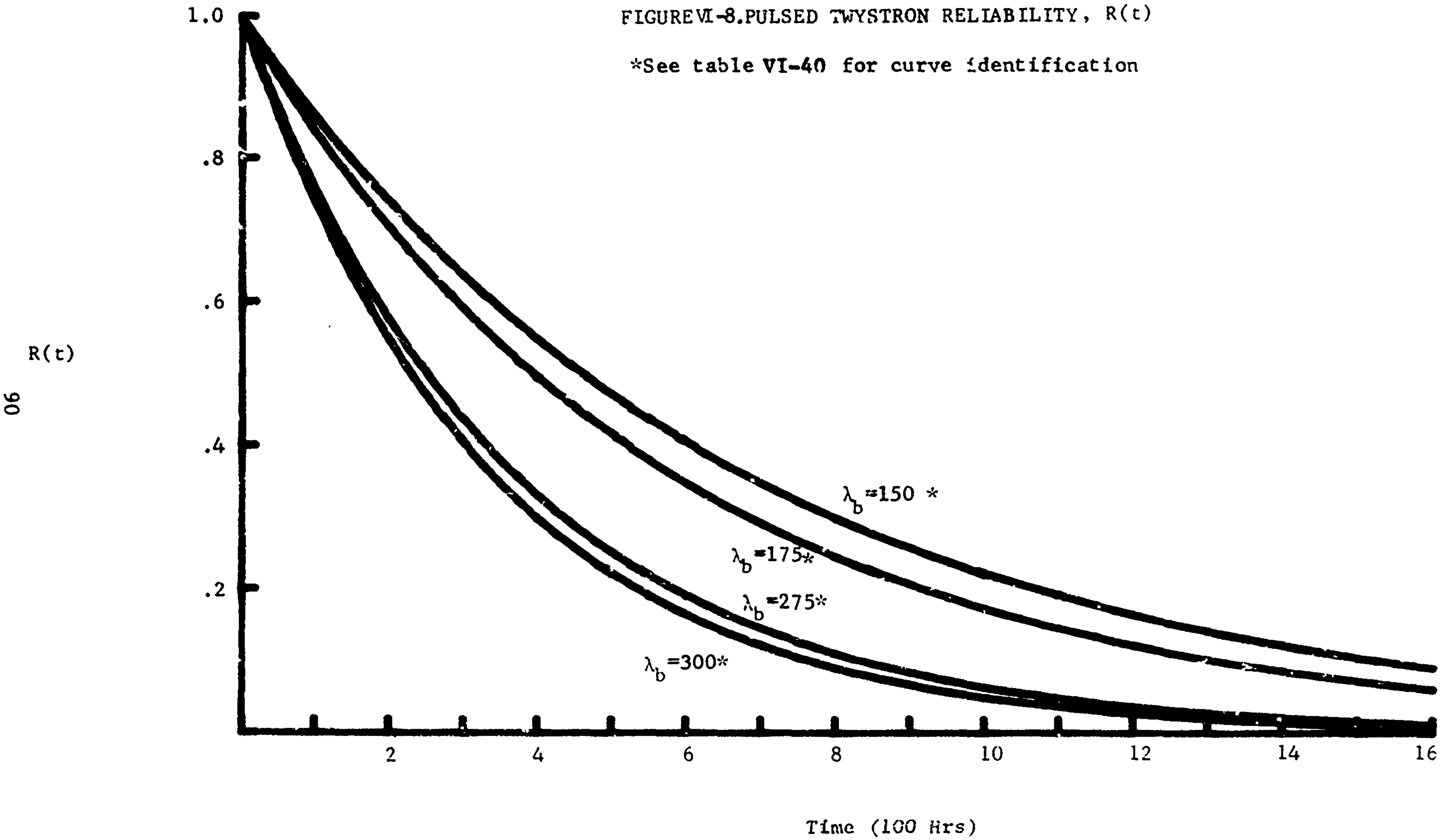


Figure VI-7 GRIDDED TUBES (PULSED) RELIABILITY, R(t)

*See table **VI-39** for curve identification

FIGURE VI-8. PULSED TWYSTRON RELIABILITY, R(t)

*See table VI-40 for curve identification



The removal criteria models are useful for the prediction of tube failure rate. The following steps are a suggested method for using the models:

Step 1. Determine the appropriate tube parameters indicated in Table VI-41 for each tube type.

Step 2. Compute the following tube parameters.

a. For CW klystrons, multiply the average power in KW by frequency in GHz to obtain a parameter with units of KW-GHz.

b. For pulsed klystrons, multiply peak power in MW by frequency in GHz to obtain a parameter with units of MW-GHz.

c. For pulsed magnetrons, multiply peak power in MW by frequency in GHz to obtain a parameter with units of MW-GHz.

d. For CW TWT's, multiply average power in W by frequency in GHz to obtain a parameter with units of W-GHz.

e. For pulsed TWT's, multiply peak power in KW by frequency in GHz to obtain a parameter in KW-GHz.

f. For pulsed Twystrons, multiply peak power in MW by frequency in GHz to obtain a parameter of MW-GHz.

Step 3. Enter the appropriate table (Table VI-42 through VI-49) to determine the importance factor, k_i, and the predicted base failure rate λ_i for each removal criterion.

Step 4. Multiply the base failure rate by the importance factor for each removal criterion and sum these products to obtain the overall base failure rate λ_b, where

$$\lambda_b = \sum_{i=1}^{n} k_i \lambda_i \qquad \text{(VI-4)}$$

Step 5. Determine the environmental and learning factors from Tables VI-31 and VI-32.

TABLE VI-41. TUBE PARAMETERS REQUIRED

REMOVAL CRITERIA MODEL

TUBE TYPE	PARAMETERS NEEDED
CW Klystrons	Average power, frequency
Pulsed Klystrons	Peak power, frequency
Magnetrons	Duty cycle, peak power, frequency
CW TWT's	Average power, frequency
Pulsed TWT's	Peak power, frequency
Gridded Tubes	Duty cycle
Twystrons	Peak power, frequency

TABLE VI-42. FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

CW KLYSTRONS

	AVERAGE POWER X FREQUENCY (KW)X(GHz)							
	BELOW 7		7-10		10-35		ABOVE 35	
REMOVAL CRITERION	λ_i*	k_i**	λ_i	k_i	λ_i	k_i	λ_i	k_i
FILAMENT	80	.28	70	.21	70	.05	50	.04
EMISSION	40	.30	50	.06	50	.16	50	.05
GASSY	100	.20	100	.16	120	.16	120	.40
MECHANICAL	150	.06	150	.06	150	.06	150	.06
FOCUSING	100	.04	100	.06	110	.08	120	.06
ARCING/SHORT	120	.12	200	.13	250	.13	350	.10
WAVEGUIDE SYSTEM	100	.04	130	.12	190	.08	210	.12
COOLING SYSTEM	80	.06	80	.20	100	.28	200	.17
π_F	.22		.42		.44		.92	

*λ_i = Failures per 10^6 Hours

**k_i = Probability of Removal Criterion Occurrence

TABLE VI-43. FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

PULSED KLYSTRONS								
	PEAK POWER X FREQUENCY (MW)X(GHz)							
	BELOW 10		10-25		25-35		ABOVE 35	
REMOVAL CRITERION	λ_i	k_i	λ_i	k_i	λ_i	k_i	λ_i	k_i
FILAMENT	70	.04	100	.03	350	.04	450	.04
EMISSION	80	.10	100	.16	150	.16	200	.12
GASSY	160	.36	180	.26	200	.28	240	.26
MECHANICAL	90	.10	100	.07	170	.06	240	.05
FOCUSING	120	.02	170	.04	220	.02	260	.02
COOLANT LEAK	100	.03	150	.06	150	.03	160	.03
ARCING/SHORT	90	.15	160	.14	220	.12	300	.10
OIL SYSTEM	90	.03	120	.08	260	.14	320	.14
WINDOW ARCING	90	.04	100	.04	200	.04	230	.16
MAGNETIC SYSTEM	130	.04	140	.04	150	.04	160	.03
WAVEGUIDE SYSTEM	120	.04	120	.02	130	.02	140	.02
COOLING SYSTEM	60	.05	120	.06	230	.05	290	.03
π_F	.69		.86		.88		.94	

TABLE VI-44. FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

MAGNETRONS				
	DUTY CYCLE BELOW .001			
	PEAK POWER X FREQUENCY (MW)X(GHz)			
	BELOW 5		5-10	
REMOVAL CRITERION	λ_i	k_i	λ_i	k_i
FILAMENT	600	.06	600	.37
EMISSION	500	.23	500	.10
GASSY	550	.30	760	.07
WINDOW	410	.01	430	.01
MECHANICAL	410	.01	430	.01
ARCING/SHORT	490	.29	420	.26
OIL SYSTEM	410	.01	674	.05
WINDOW ARCING	410	.01	430	.01
MAGNETIC SYSTEM	410	.01	430	.01
WAVEGUIDE SYSTEM	410	.01	600	.05
COOLING SYSTEM	410	.01	590	.06
π_F	.80		.80	

TABLE VI-45. FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

MAGNETRONS

DUTY CYCLE ABOVE .001

PEAK POWER X FREQUENCY (MW)X(GHz)

REMOVAL CRITERION	BELOW 5 λ_i	BELOW 5 k_i	5-10 λ_i	5-10 k_i	ABOVE 10 λ_i	ABOVE 10 k_i
FILAMENT	435	.04	435	.21	435	.37
EMISSION	300	.19	310	.12	320	.05
GASSY	650	.30	770	.26	890	.20
WINDOW	450	.02	460	.01	470	.01
MECHANICAL	600	.05	600	.03	600	.01
ARCING/SHORT	500	.22	500	.18	500	.13
OIL SYSTEM	700	.03	700	.05	700	.08
MAGNETIC SYSTEM	440	.01	460	.01	470	.01
WAVEGUIDE SYSTEM	600	.08	610	.07	620	.07
COOLING SYSTEM	700	.03	700	.02	700	.02
WINDOW ARCING	600	.03	600	.04	600	.05
Π_F	.33		.82		.76	

TABLE VI-46. FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

CW TWT'S

	AVERAGE POWER X FREQUENCY (W)X(GHz)			
	BELOW 100		ABOVE 100	
REMOVAL CRITERION	λ_i	k_i	λ_i	k_i
FILAMENT	140	.15	110	.25
EMISSION	80	.43	205	.25
GASSY	70	.31	900	.34
FOCUSING	70	.01	200	.01
COOLANT LEAK	70	.01	200	.01
ARCING/SHORT	70	.06	320	.11
WINDOW ARCING	70	.01	200	.01
MAGNETIC SYSTEM	70	.01	200	.01
WAVEGUIDE SYSTEM	70	.01	200	.01
Π_F	.71			

TABLE VI-47. FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

PULSED TWT'S				
	PEAK POWER X FREQUENCY (KW)X(GHz)			
	BELOW 100		ABOVE 100	
REMOVAL CRITERION	λ_i	k_i	λ_i	k_i
FILAMENT	142	.06	310	.04
EMISSION	90	.70	310	.09
GASSY	160	.06	310	.21
WINDOW	200	.01	310	.12
FOCUSING	200	.01	310	.01
COOLANT LEAK	200	.01	310	.01
ARCING/SHORT	160	.10	310	.17
WINDOW ARCING	200	.01	310	.01
MAGNETIC SYSTEM	200	.01	310	.01
WAVEGUIDE SYSTEM	120	.02	310	.21
COOLING SYSTEM	200	.01	310	.12
Π_F	.99			

TABLE VI-48 FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

PULSED TWYSTRONS

PEAK POWER X FREQUENCY (MW)X(GHz)

REMOVAL CRITERION	BELOW 10 λ_i	BELOW 10 k_i	10-20 λ_i	10-20 k_i	20-30 λ_i	20-30 k_i	ABOVE 30 λ_i	ABOVE 30 k_i
FILAMENT	150	.07	175	.08	275	.01	300	.01
EMISS[illegible]	150	.04	175	.14	250	.21	300	.16
GA[illegible]	150	.38	175	.29	390	.30	300	.29
WINDOW	150	.01	175	.01	275	.01	300	.18
FOCUSING	150	.04	175	.01	370	.12	300	.01
COOLANT LEAK	150	.04	175	.14	275	.02	300	.07
OIL SYSTEM	150	.07	175	.14	275	.15	300	.01
HEATER SEAL	150	.01	175	.01	275	.01	300	.01
WINDOW ARCING	150	.11	175	.01	275	.02	300	.01
ARCING/SHORT	150	.11	175	.01	275	.05	300	.13
MAGNETIC SYSTEM	150	.04	175	.14	275	.02	300	.07
WAVEGUIDE SYSTEM	150	.07	175	.01	275	.01	300	.01
COOLING SYSTEM	150	.01	175	.01	200	.07	300	.04
π_F	1.0		1.0		.89		1.0	

TABLE VI-49 FAILURE RATES AND IMPORTANCE FACTORS BY REMOVAL CRITERION

GRIDDED TUBES

REMOVAL CRITERION	DUTY CYCLE BELOW 0.0075 λ_i	k_i	0.0075-0.0150 λ_i	k_i	0.0150-0.0220 λ_i	k_i
FILAMENT	160	.03	160	.04	160	.02
EMISSION	90	.15	120	.18	350	.50
GASSY	200	.14	350	.05	550	.03
ARCING/SHORT	200	.55	240	.65	540	.40
WAVEGUIDE SYSTEM	190	.06	240	.03	310	.02
COOLING SYSTEM	210	.07	250	.05	500	.03
π_F	.96		.90		.93	

Step 6. Obtain the part failure rate as the product of the base failure rate, the environmental factor, and the learning factor.

$$\lambda'_p = \lambda_b \pi_E \pi_L \qquad \text{(VI-5)}$$

The prediction of the failure rate will be somewhat higher than the failure rate from the overall failure rate model as it is based on data from only those tubes which have failed. To obtain a failure rate which will take into account all tubes in service the part failure rate, λ'_p, computed above should be multiplied by the Π_F factor found at the bottom of Table VI-42 through VI-49. Tables VI-46 and VI-47 do not have a Π_F factor in the right hand column because the overall failure rate models and the removal criterion models for TWT's do not cover the same parameter ranges. A new expression for part failure rate is

$$\lambda_p = \lambda'_p \pi_F. \qquad \text{(VI-6)}$$

The products of removal criterion failure rates and importance factors obtained in Step 4 can be used to determine the importance of each removal criterion to tube reliability. These individual products can be ranked to determine the order of their importance. If a designer can justify the elimination or reduction of frequency of a removal criterion's occurrence he may revise the importance (k) factors. These may then be used with the failure rates from Tables VI-42 through VI-49 to obtain a revised part failure rate. The revised importance factors must sum to unity.

H. Example Application of Models

The FAA has recently specified a new air surveillance radar system [5] to be designed and built. The new system is the ASR-8. It will use a high power klystron as the final transmitter stage. The klystron will operate in a frequency band centered around 2.8 GHz at one megawatt peak power. The failure rate of pulsed klystrons were modeled as a function of peak power times frequency. The peak power times frequency parameter for the ASR-8 klystron is 2.8 MW x GHz. The learning factor (π_L) from Table VI-32 is 1.0 due to the assumption that an existing klystron will be used in the ASR-8. The environmental factor (π_E) from Table VI-31 is 1.0 as the system is a fixed ground based installation. The predicted overall base failure rate (λ_b) is 80 failures per million hours (from Table VI-35) the part failure rate using (VI-1) is

$$\lambda_p = \pi_E \pi_L \lambda_b$$

$$= (1.0)\ (1.0)\ (80)$$

$$= 80 \text{ failures}/10^6 \text{ hours}$$

The removal criterion model is based on the same parameter (peak power times frequency) as the overall failure rate model used in the above paragraph. From Table VI-43, the failure rates (λ_i) and importance factors (k_i) in Table VI-50 are taken.

The fourth column in Table VI-50 is the product of the failure rate (λ_i) and the importance factor (k_i) for the listed removal criterion. The product, $\lambda_i \times k_i$, is the relative contribution for removal criterion, i, to the overall failure rate (λ_b). The sum of these relative contributions is 115.6 failures per million hours which is the overall failure rate (λ_b) of the tubes that have failed. The factor, π_F, from Table VI-43 is 0.69 for the ASR-8 klystron. Using (VI-5) and (VI-6), the tube failure rate is

$$\lambda_p = \pi_F \pi_E \pi_L \lambda_b \qquad \text{(IV-7)}$$

$$= (.69)\ (1.0)\ (1.0)\ (115.6)$$

$$= 80 \text{ failures}/10^6 \text{ hours}$$

TABLE VI-50. REMOVAL CRITERIA MODEL FOR THE ASR-8 KLYSTRON

Removal Criterion	Failure Rate λ_i	Importance k_i	Contribution of Removal Criterion $\lambda_i \times k_i$
Filament	70	.04	2.8
Emission	80	.1	8.0
Gassy	160	.36	57.6
Mechanical	90	.1	9.0
Focusing	120	.02	2.4
Coolant Leak	100	.03	3.0
Arcing/Short	90	.15	13.5
Oil System	90	.03	2.7
Window Arcing	90	.04	3.6
Magnetic System	130	.04	5.2
Waveguide System	120	.04	4.8
Cooling System	60	.05	3.0

One interesting item in Table VI-50 is the relative contribution of the gassy removal criterion. The failure rate for the gassy removal criterion is 160 and the importance factor is 0.36 resulting in a relative contribution of 57.6 which is practically half of the base failure rate of 115.6 failures per million hours. To reduce the expected failure rate of the ASR-8 klystron the failure rate and/or frequency of occurrence (importance) must be reduced for the gassy removal criterion.

I. Utility of Models

The agencies that purchase systems employing microwave tubes are interested not only in the initial cost of a system but also in the cost of operating the system for a period of several years. Included in the yearly operational cost for a group of systems is the cost of replacing the microwave tubes. Many of these tubes are highly priced items, ranging from $10,000 to $50,000 each, with mean lifes of only a few thousand hours. For example, if 20 systems each use a tube costing $31,000 with a mean life of 3500 hours, then the expected yearly tube replacement cost assuming 2000 operating hours per system per year will be $354,000.

In order to reduce the expected annual tube replacement cost for a proposed system certain protective features could be included in the system's specifications. The nature of these protective features would depend upon the problems expected to occur in the operation of that specific system. The "k" factors in the removal criteria model indicate the predominate removal criteria for specific tube types with certain operating parameters. In many cases one of the predominate removal criteria will have a higher failure rate than most other criteria. A protective feature could be specified to reduce the frequency of occurrence and/or failure rate of such a removal criterion resulting in an overall failure rate decrease and, therefore, a system operating cost decrease.

VII. COST-RELIABILITY ANALYSIS

A. Objective

The objective of this portion of the research was to develop a decision making procedure to determine if research to improve tube reliability is worthwhile from a cost reduction point of view. Reliability improvement usually requires an investment in research, as well as an increase in the price of the tube. The price increase is due to higher quality materials and equipment and/or improved manufacturing procedures. The economic feasibility of the research depends on the reliability improvement and the increase in cost which would result from the research.

The high cost of microwave tubes makes reliability improvement seem attractive. To be cost-effective, however, the cost of the improvement must be offset by an overall decrease in operating or replacement cost. This improvement involves research to lower the tube failure rate. The lower failure rate should be such that the savings from buying fewer tubes pays for the possible increased cost of the improved tube, and recovers the research investment within a reasonable length of time.

Research may be undertaken in two ways. The first is research in the various general technology areas with which high failure rates are associated. This is fundamental research which should develop techniques and materials to improve reliability applicable to a wide range of tubes. The direction and amount of research in this area should be determined by considering the overall frequency of occurrence of the various removal criteria.

The second area of research involves reliability improvement for specific tubes. Rather than basic research on fundamental aspects of tube design, individual tubes should be studied in depth. This involves studying the manufacturing process to determine the cause of the removal criteria with the highest frequency of occurrence. Known methods should be employed to reduce failures in problem areas indicated by the reliability study. Emphasis on quality control and materials standards should be increased.

The results from such a study should be a tube that lasts longer, but probably costs more. In each case analysis should be undertaken to determine whether the research would be cost effective, based on best estimates of the possible savings because of reliability, improvement, and its cost.

B. Methodology

1. Identification of Candidate Tubes

In identifying which tubes are the best candidates for reliability improvement, the tubes can be ranked by several different parameters. Each of these parameters has merits as a measure of cost-benefit of reliability improvement. The principal parameters that should be considered are the following:

1) COST/SOCKET/KW/M HR
2) TOTAL COST/KW/M HR
3) COST/SOCKET/M HR
4) TOTAL COST/M HR
5) COST/SOCKET/KW/YEAR
6) TOTAL COST/KW/YEAR
7) COST/SOCKET/YEAR
8) TOTAL COST/YEAR

where: "KW" indicates a kilowatt of average power, "M HR" indicates 10^6 hours of operation, "Total" indicates the number of installations (sockets). Cost and failure rate are common to all of the parameters.

Information on the above parameters was obtained on each of the tubes included in the study, and an analysis was done to establish rankings. Tables VII-1 through VII-8 contain the ranking of tubes by each of these parameters.

*Tables VII-5 through VII-8 have failure rate in units of failures per hundred years due to a computer program requirement.

Table VII-1

MICROWAVE TUBE COST-RELIABILITY RANKING BASED ON COST PER SOCKET PER MILLION HOURS PER KW OF AVERAGE POWER

TUBE NUMBER	TYPE	AVERAGE POWER (WATTS)	UNIT COST** (DOLLARS)	FAILURES PER MILLION HRS*	FIELD INSTALLATIONS	COST PER SOCKET PER MILLION HRS PER KW OF AVERAGE POWER (K$)/(M HRS)/(KW)
4KT00	KLY	1200	5703	681	9	3236
VA884C	KLY	1000	2940	419	197	1231
4K3SK	KLY	1000	3268	75	18	620
VA856D	KLY	2000	9500	73	11	346
4KMP10000LF	KLY	4600	15008	78	10	254
3K50000LA	KLY	10000	3106	776	10	241
Z5(1)A	KLY	15000	15857	207	11	218
4KM50LB	KLY	12500	13555	222	4	173
A7600	KLY	75000	32661	389	2	169
ZM3038A	KLY	30000	15961	294	21	156
4KM5JSJ	KLY	12000	18364	91	4	139
4KM5JSK	KLY	12000	14832	68	33	84
3KM3000LA	KLY	2300	4000	42	37	73
VA8CJE	KLY	10000	9938	74	5	66
L3035	KLY	6600	5166	84	98	65
4KM3000LR	KLY	2000	3419	36	109	61
L3250	KLY	15000	7709	95	27	48
3K5000LLF	KLY	10000	3425	130	2	47
3KM5000PA	KLY	20000	7434	122	18	45
3KM5000PA1	KLY	23000	6368	144	12	39
3K3000LQ	KLY	2300	2653	28	65	37
3KM300LA	KLY	100000	37140	95	5	35
3K210000LO	KLY	76000	11857	193	21	30
L3403	KLY	75000	15112	144	74	29
4KM50000LC	KLY	10500	3130	98	11	29
3KM50000PA2	KLY	23000	3565	181	33	28
4K5000LLQ	KLY	10000	5155	48	66	24
4KM50LC	KLY	12500	6322	45	6	21
4KM5000JLF	KLY	11500	2950	83	126	21
4KM170000LA	KLY	75000	48000	26	4	16
VA842	KLY	75000	20904	50	18	13
7256	MAG	40	558	603	277	8411
4J0615	MAG	1300	3435	678	22	1775
4798	MAG	450	1175	575	240	1501
5586	MAG	400	378	995	46	940
QK327A	MAG	2500	3000	456	23	547
QK338A	MAG	4500	1260	474	57	132
2041	TET	3000	9554	188	22	598
6952	TET	4000	3307	460	11	388
7835	TET	60000	39168	183	9	116
VTR5210A	TWT	10	2398	216	51	51796
ZM3167	TWT	10	2053	100	40	28530
MA2002A	TWT	250	6192	250	6	6192
VA139D	TWT	70	3563	93	7	4733
VA145E	TWY	5000	22649	886	15	4820
VA145H	TWY	10000	24692	583	4	1439
VA913A	TWY	10000	22000	310	13	681

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COSTS

*FAILURE RATE IS THE ARITHMETIC MEAN OF THE RADIANT HOURS ON ALL FAILED TUBES

Table VII-2

MICROWAVE TUBE COST-RELIABILITY-RANKING BASED ON TOTAL COST PER MILLION HOURS PER KW OF AVERAGE POWER

TUBE NUMBER	TYPE	AVERAGE POWER (WATTS)	UNIT COST** (DOLLARS)	FAILURES PER MILLION HRS*	FIELD INSTALLATIONS	TOTAL COST PER MILLION HRS PER KW OF AVERAGE POWER (K$)/(M HRS)/(KW)
VA888E	KLY	1000	2940	419	197	242676
4K3CC	KLY	1200	5703	681	9	29128
4K3SK	KLY	1000	9268	75	18	11161
4KM300LLF	KLY	2000	3419	36	109	6708
L3035	KLY	6600	5166	84	90	5917
VA8569	KLY	2800	9530	73	11	3014
ZM3038A	KLY	30000	15961	294	21	3284
4KM50SK	KLY	12800	14832	68	33	2773
3KM300LLA	KLY	2300	4000	42	37	2702
4KM5000LF	KLY	11500	2950	83	126	2682
4KMP10000LF	KLY	4600	15000	78	10	2543
3K2000LQ	KLY	2800	2653	28	65	2414
3K50000LA	KLY	10000	3166	776	10	2410
Z5010A	KLY	15000	15857	207	11	2407
L3403	KLY	75000	15112	144	74	2147
4K50000LQ	KLY	10000	5155	48	66	1633
L3250	KLY	15000	7729	95	27	1318
3KM50000PA2	KLY	23000	3565	181	33	925
3KM50000PA	KLY	20000	7434	127	18	816
4KM50LH	KLY	13500	19555	222	4	694
3K210000LQ	KLY	76000	11857	197	21	632
4KM50SJ	KLY	12000	18364	91	4	557
3KM50000PA1	KLY	23000	6363	144	12	478
X780O	KLY	75000	32661	389	2	338
VA800E	KLY	10000	8978	74	5	330
4KM50000LQ	KLY	10500	3130	98	11	321
VA842	KLY	75000	20904	50	18	250
3KM300LA	KLY	100000	37140	95	5	176
4KM50LC	KLY	13500	6322	45	6	126
3K50000LF	KLY	10000	3425	138	2	94
4KM170000LA	KLY	75000	45000	26	4	66
7256	MAG	40	558	603	277	2338082
8798	MAG	450	1175	575	240	360333
5586	MAG	400	378	995	46	43252
4J6615	MAG	1300	3405	678	22	39068
QK327A	MAG	2500	3600	456	23	12585
QK334A	MAG	4500	1260	474	57	7565
2041	TET	3000	9554	168	22	13171
6952	TET	4000	3307	460	11	4183
7835	TET	60000	38168	183	9	1047
VTF5210A	TWT	10	2398	216	51	2641636
ZM3167	TWT	10	2053	100	40	821200
MA2001A	TWT	250	6192	250	6	37152
VA1360	TWT	70	3563	93	7	33135
VA145E	TWY	5000	22609	886	15	60307
VA913A	TWY	10000	22600	310	13	8865
VA145M	TWY	10000	24692	583	4	5758

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COST

*FAILURE RATE IS THE ARITHMETIC MEAN OF THE RADIANT HOURS ON ALL FAILED TUBES

Table VII-3

MICROWAVE TUBE COST-RELIABILITY RANKING BASED ON COST PER SOCKET PER MILLION HOURS

TUBE NUMBER	TYPE	AVERAGE POWER (WATTS)	UNIT COST** (DOLLARS)	FAILURES PER MILLION HRS*	FIELD INSTALLATIONS	COST PER SOCKET PER MILLION HRS (K$)/(M HRS)
X7800	KLY	75000	32661	389	2	12705
ZM3038A	KLY	30000	15951	294	21	4692
4K3CC	KLY	1200	5723	661	9	3883
3KM300LA	KLY	100000	27148	95	5	3528
2SL10A	KLY	15800	15857	207	11	3282
3K50000LA	KLY	10000	3106	776	10	2410
4KM50LB	KLY	13500	19555	222	4	2343
3K21000LO	KLY	76000	11857	193	21	2288
L3403	KLY	75000	15112	144	74	2176
4KM50SJ	KLY	12000	19364	91	4	1871
4KM170000LA	KLY	75000	49600	26	4	1240
VA889E	KLY	1000	2948	419	197	1231
4KMP10000LF	KLY	4600	15000	76	10	1170
VA842	KLY	75000	28934	50	18	1045
4KM50SK	KLY	12000	14832	68	33	1000
3KM50000PA1	KLY	23000	6364	144	12	916
3KM50000PA	KLY	20000	7474	122	18	986
L3250	KLY	15800	7709	95	27	732
VA856B	KLY	2000	9500	73	11	693
VA800E	KLY	10000	8938	74	5	661
3KM50000PA2	KLY	23000	3565	181	32	645
4K3SK	KLY	1000	8260	75	10	628
3K50000LF	KLY	16000	3425	138	2	472
L3035	KLY	6680	5166	84	90	433
4KM50000LQ	KLY	10500	3138	98	11	386
4KM50LC	KLY	13500	6322	45	6	284
4K50000LQ	KLY	10000	5155	48	66	247
4KM50000LR	KLY	11500	2950	83	126	244
3KM3000LA	KLY	2300	4000	42	37	160
4KM3000LR	KLY	2000	3419	36	109	123
3K3000LQ	KLY	2800	2653	28	65	74
40C615	MAG	1300	3405	670	22	2300
QK327A	MAG	2500	1000	456	23	1360
8798	MAG	450	1175	575	240	675
QK338A	MAG	4500	1260	474	57	597
5586	MAG	400	370	995	46	376
7256	MAG	40	558	603	277	336
2041	TET	3000	9554	188	22	1796
6952	TET	4000	3307	460	11	1521
7935	TRI	60000	38168	183	9	6984
MA2001A	TWT	250	6192	258	6	1548
VTR5210A	TWT	10	2398	216	51	517
VA1393	TWT	70	3563	93	7	331
ZM3167	TWT	10	2053	180	40	205
VA145E	TWY	5000	22699	836	15	28182
VA145H	TWY	10000	24692	583	4	14395
VA913A	TWY	10000	22000	310	13	6820

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COSTS

*FAILURE RATE IS THE ARITHMETIC MEAN OF THE RADIANT HOURS ON ALL FAILED TUBES

Table VII-4

MICROWAVE TUBE COST-RELIABILITY RANKING BASED ON TOTAL COST PER MILLION HOURS

TUBE NUMBER	TYPE	AVERAGE POWER (WATTS)	UNIT COST** (DOLLARS)	FAILURES PER MILLION HRS*	FIELD INSTALLATIONS	TOTAL COST PER MILLION HRS (K$)/(M HRS)
VA885E	KLY	1000	2940	419	197	242676
L3403	KLY	75000	15212	144	74	161833
ZM3638A	KLY	30000	15961	294	21	98543
3K210000LQ	KLY	76000	11857	193	21	40856
L3035	KLY	6600	5166	84	96	39854
Z5010A	KLY	15800	15357	237	11	36186
4K3CC	KLY	1200	5703	681	9	34953
4KM50SK	KLY	12000	14832	68	33	33283
4KM50000LR	KLY	11500	2958	83	126	30851
X7800	KLY	75000	32661	389	2	25410
3K50000LA	KLY	16000	3106	776	10	24182
3KM50000PA2	KLY	23000	3565	181	33	21293
L3250	KLY	15000	7709	95	27	19773
VA842	KLY	75000	23934	50	18	18813
3KM300LA	KLY	100000	37140	95	5	17641
4K50000LQ	KLY	10000	5155	48	56	16331
3KM50000PA	KLY	20000	7434	122	18	15325
4KM3000LR	KLY	2000	3419	36	109	13416
4KMP10000LF	KLY	4600	15000	70	10	11788
4K3SK	KLY	1000	8208	75	18	11161
3KM50000PA1	KLY	23000	6368	145	12	11083
4KM50LB	KLY	12500	10555	222	4	9372
VA856B	KLY	2800	9588	73	11	7628
4KM50SJ	KLY	12000	18364	91	4	6684
3KM3000LA	KLY	2300	4000	42	37	6216
4KM170000LA	KLY	75000	48000	26	4	4992
3K3000LQ	KLY	2000	2653	28	65	4828
4KM50000LQ	KLY	10500	3130	98	11	3374
VA800E	KLY	16000	8938	74	5	3387
4KM50LC	KLY	13500	6322	45	6	1706
3K50000LF	KLY	16000	3425	138	2	945
8798	MAG	450	1175	575	240	162158
7256	MAG	40	558	603	277	93203
4J0625	MAG	1300	3435	678	22	50788
QK338A	MAG	4500	1260	474	57	34842
QK327A	MAG	2500	3000	456	23	31464
5586	MAG	400	378	995	46	17301
2041	TET	3000	9554	188	22	39515
6952	TET	4000	3307	460	11	16733
7835	TRI	60000	38168	183	9	62862
VTR5210A	TWT	10	2398	215	51	26416
MA2031A	TWT	250	6192	250	6	9288
ZM3167	TWT	10	2053	106	40	8212
VA138D	TWT	70	3563	93	7	2319
VA145E	TWY	5000	22689	886	15	381536
VA913A	TWY	10000	22600	310	13	88660
VA145H	TWY	10000	24692	583	4	57581

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COSTS

*FAILURE RATE IS THE ARITHMETIC MEAN OF THE RADIANT HOURS ON ALL FAILED TUBES

Table VII-5

MICROWAVE TUBE COST-RELIABILITY RANKING BASED ON COST PER SOCKET PER HUNDRED YEARS PER KW OF AVERAGE POWER

TUBE NUMBER	TYPE	AVERAGE POWER (WATTS)	UNIT COST** (DOLLARS)	FAILURES PER HUNDRED YRS*	FIELD INSTALLATIONS	COST PER SOCKET PER HUNDRED YRS PER KW OF AVERAGE POWER (K$)/(C YRS)/(KW)
4K3SK	KLY	1000	8268	39	18	322
4K3CC	KLY	1200	5793	67	9	318
VA656B	KLY	2000	9500	61	11	289
VA888E	KLY	1003	2948	77	197	226
Z5010A	KLY	15000	15857	189	11	199
L3035	KLY	6600	5166	240	90	187
4KMP10000LF	KLY	4600	15003	45	10	146
ZM3038A	KLY	30000	15961	191	21	101
4KM50LB	KLY	13500	10555	129	[illegible]	100
4KM50SJ	KLY	12000	10364	48	4	73
X780D	KLY	75000	32661	135	2	58
3KM3000LA	KLY	2300	4008	33	37	57
4KM50SK	KLY	12000	14832	45	33	55
4KM3000LR	KLY	2800	3419	27	109	46
3KM300LA	KLY	100000	37148	79	5	29
VA880E	KLY	10000	8938	29	5	25
3KM50000PA	KLY	20000	7434	69	18	25
3KM50000PA1	KLY	23000	6368	86	12	23
L3250	KLY	15000	7709	42	27	21
L3403	KLY	75000	15112	109	74	21
3KM50000PA2	KLY	23000	3565	124	33	19
3K3000LQ	KLY	2000	2653	15	65	19
3K210000LQ	KLY	76000	11857	128	21	18
3K50000LA	KLY	10000	3106	60	10	18
4KM50000LQ	KLY	16500	3138	59	11	17
4KM170000LA	KLY	75000	48008	22	4	14
4KM50LC	KLY	13500	6322	38	6	14
4K50000LQ	KLY	10000	5155	28	66	14
4KM50000LF	KLY	12500	2950	49	126	12
3K50000LF	KLY	10000	3425	35	2	11
VA842	KLY	75000	28904	10	18	2
7256	MAG	40	558	267	277	3724
8798	MAG	450	1175	261	240	681
QK327A	MAG	2500	3000	413	23	495
5586	MAG	400	378	414	46	391
406615	MAG	1300	3405	103	22	269
QK338A	MAG	4500	1268	211	57	59
2041	TET	3000	9554	114	22	363
6952	TET	4000	3307	190	11	157
7835	TRI	60000	38168	67	9	42
VTR5210A	TWT	10	2398	480	51	115104
ZM3167	TWT	10	2053	22	40	4516
VA138D	TWT	70	3563	79	7	4821
MA2001A	TWT	250	6192	124	6	3071
VA913A	TWY	10000	22000	145	13	318
VA145E	TWY	5000	22689	62	15	281
VA145H	TWY	10000	24692	38	4	93

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COSTS
*FAILURE RATE IS BASED ON THE AVERAGE TIME (YEARS) FOR ALL FAILED TUBES

Table VII-6

MICROWAVE TUBE COST-RELIABILITY RANKING BASED ON TOTAL COST PER HUNDRED YEARS PER KW OF AVERAGE POWER

TUBE NUMBER	TYPE	AVERAGE POWER (WATTS)	UNIT COST** (DOLLARS)	FAILURES PER HUNDRED YRS*	FIELD INSTALLATIONS	TOTAL COST PER HUNDRED YRS PER KW OF AVERAGE POWER (K$)/(C YRS)/(KW)
VA888E	KLY	1000	2940	77	197	64596
L3035	KLY	6600	5166	240	90	16906
4K3SK	KLY	1000	9268	39	18	5804
4KM3000LR	KLY	2000	3419	27	109	5931
VA856B	KLY	2000	9500	61	11	3167
4K3CC	KLY	1200	5703	67	9	2865
Z5013A	KLY	15000	15857	189	11	2197
ZM3038A	KLY	30000	15961	191	21	2133
3KM3000LA	KLY	2300	4000	33	37	2123
4KM50SK	KLY	12000	14832	45	32	1835
L3403	KLY	75000	15112	109	74	1625
4KM50000LR	KLY	11500	2950	49	126	1583
4KMP10000LF	KLY	4600	15000	45	10	1467
3K3000LQ	KLY	2000	2653	15	65	1293
4K50000LQ	KLY	16000	5155	28	66	952
3KM50000PA2	KLY	23000	3565	124	33	634
L3250	KLY	15000	7709	42	27	582
3KM50000PA	KLY	20000	7434	69	18	461
4KM55LB	KLY	13500	10555	129	4	403
3K210000LQ	KLY	76000	11857	120	21	393
4KM58SJ	KLY	12000	18364	48	4	293
3KM50000PA1	KLY	23000	6368	96	12	285
4KM50000LQ	KLY	16500	3130	59	11	193
3K50000LA	KLY	10000	3106	60	10	186
3KM3000LA	KLY	100000	37140	79	5	146
VA800E	KLY	10000	8938	29	5	129
X780D	KLY	75000	32661	135	2	117
4KM50LC	KLY	13500	6322	30	6	84
4KM170000LA	KLY	75000	48000	22	4	56
VA842	KLY	75000	20994	10	18	58
3K50000LF	KLY	16000	3425	35	2	23
7256	MAG	40	558	267	277	1031728
8798	MAG	450	1175	261	240	163559
5586	MAG	400	378	414	46	17996
QK327A	MAG	2500	3000	413	23	11398
4J6615	MAG	1300	3405	103	22	5935
QK338A	MAG	4500	1260	211	57	3367
2041	TET	3000	9554	114	22	7987
6952	TET	4000	3307	190	11	1727
7835	TRI	60000	38168	67	9	363
VTF5211A	TWT	10	2398	480	51	5870384
ZM3167	TWT	10	2033	22	40	180663
VA138D	TWT	70	3563	79	7	28147
MA2001A	TWT	250	6192	124	6	18427
VA145E	TWY	5000	22689	62	15	4220
VA913A	TWY	10005	22000	145	13	4146
VA145H	TWY	10000	24692	38	4	375

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COSTS

*FAILURE RATE IS BASED ON THE AVERAGE TIME (YEARS) FOR ALL FAILED TUBES

Table VII-7

MICROWAVE TUBE COST-RELIABILITY RANKING BASED ON COST PER SOCKET PER HUNDRED YEARS

TUBE NUMBERS	TYPE	AVERAGE POWER (WATTS)	UNIT COST** (DOLLARS)	FAILURES PER HUNDRED YRS*	FIELD INSTALLATIONS	COST PER SOCKET PER HUNDRED YRS (K$)/(C YRS)
X780D	KLY	75000	32661	135	2	4459
ZM3038A	KLY	30000	15961	191	21	3848
Z5010A	KLY	15000	15857	189	11	2996
3KM300LA	KLY	100000	37140	79	5	2934
L3403	KLY	75000	15112	109	74	1647
3K210000LQ	KLY	76000	11857	120	21	1422
4KM50LB	KLY	12500	10559	129	4	1361
L3035	KLY	6600	5166	240	90	1239
4KM170000LA	KLY	75000	48000	22	4	1056
4KM50SJ	KLY	12000	19364	44	4	881
4KMP10000LF	KLY	4600	15000	45	10	675
4KM50SK	KLY	12000	14832	45	33	667
VA856B	KLY	2000	9500	61	11	579
3KM50000PA1	KLY	23000	6368	86	12	547
3KM50000PA	KLY	20000	7434	69	18	512
3KM50000PA2	KLY	23000	3565	124	33	442
4K3CC	KLY	1200	5703	67	9	382
L3250	KLY	15000	7709	42	27	323
4K3SK	KLY	1000	8268	39	[illegible]	322
VA800E	KLY	10000	8938	29	5	259
VA888E	KLY	1000	2948	77	197	226
VA842	KLY	75000	20904	10	18	209
4KM50LC	KLY	13500	6322	38	6	189
3K50000LA	KLY	10000	3106	60	10	186
4KM50000LQ	KLY	10500	3130	59	11	184
4KM50000LP	KLY	11500	2950	49	126	144
4K50000LQ	KLY	10000	5155	28	66	144
3KM3000LA	KLY	2300	4860	33	37	132
3K50000LF	KLY	10000	3425	35	2	119
4KM3000LP	KLY	2000	3419	27	109	92
3K3000LQ	KLY	2000	2653	15	65	39
QK327A	MAG	2500	3600	413	23	1239
4J615	MAG	1300	3405	103	22	350
8798	MAG	450	1175	261	240	386
QK338A	MAG	4500	1260	211	57	265
5586	MAG	400	378	414	46	156
7256	MAG	40	558	267	277	148
2041	TET	3000	9554	114	22	1089
6952	TET	4000	3337	190	11	628
7835	TRI	60000	38168	67	9	2557
VTR5211A	TWT	10	2398	480	51	1151
MA2001A	TWT	250	6192	124	6	767
VA1380	TWT	73	3563	79	7	281
ZM3167	TWT	10	2053	22	40	45
VA913A	TWY	10000	22000	145	13	3198
VA145E	TWY	5000	22689	62	15	1406
VA145H	TWY	10000	24692	38	4	938

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COSTS
*FAILURE RATE IS BASED ON THE AVERAGE TIME (YEARS) FOR ALL FAILED TUBES

Table VII-8

MICROWAVE TUBE COST-RELIABILITY RANKING BASED ON TOTAL COST PER HUNDRED YEARS

TUBE NUMBER	TYPE	AVERAGE POWER (WATTS)	UNIT COST ** (DOLLARS)	FAILURES PER HUNDRED YRS*	FIELD INSTALLATIONS	TOTAL COST PER HUNDRED YRS
L3403	KLY	75000	15112	109	74	121893
L3035	KLY	6600	5166	240	98	111585
ZM3019A	KLY	30000	15961	191	21	64019
VA889L	KLY	1000	2940	77	197	44096
Z5010A	KLY	15000	15357	189	11	32966
3K210000LQ	KLY	76000	11857	120	21	29879
4KM50SK	KLY	12000	14932	45	32	22025
4KM50000LF	KLY	22500	2950	49	126	18213
3KM300LA	KLY	100000	37140	79	5	14670
3KM50000PA2	KLY	23000	3565	124	33	14587
4KM3000LR	KLY	2000	3419	27	109	10862
4K50000LQ	KLY	10000	5155	28	66	9526
3KM50000PA	KLY	20000	7434	69	18	9223
X7800	KLY	75000	32661	138	2	8810
L3250	KLY	15000	7759	42	27	8712
4KMP10000LF	KLY	4600	15000	45	10	6750
3KM50000PA1	KLY	23000	6368	86	12	6571
VA8568	KLY	2000	9500	61	11	6374
4K3SK	KLY	1000	9258	39	18	5804
4KM50LQ	KLY	13500	10555	129	4	5446
3KM3000LA	KLY	2300	4000	33	37	4894
4KM17000LA	KLY	75000	48000	22	4	4224
VA842	KLY	75000	20964	10	18	3762
4KM5000	KLY	12000	18364	48	4	3525
4K3CC	KLY	1200	5703	67	9	3438
3K3000LQ	KLY	2000	2653	15	65	2586
4KM50000LQ	KLY	10500	3130	59	11	2031
3K50000LA	KLY	10000	3136	60	10	1263
VA800E	KLY	16000	8938	29	5	1296
4KM50LC	KLY	13500	6322	30	6	1137
3K50000LF	KLY	10000	3425	35	2	239
8798	MAG	450	1175	261	240	73601
7256	MAG	40	558	267	277	41269
QK327A	MAG	2500	3000	413	23	28497
QK338A	MAG	4500	1260	211	57	15154
400615	MAG	1300	3405	103	22	7715
5586	MAG	400	378	414	46	7198
2041	TET	3000	9554	114	22	23961
6952	TET	4000	3307	190	11	6911
7835	TRI	60000	38168	67	9	23015
VTF5210A	TWT	10	2398	480	51	58703
MA2001A	TWT	250	6192	124	6	4606
VA1380	TWT	73	3563	79	7	1970
ZM3167	TWT	10	2053	22	40	1806
VA913A	THY	10000	22009	145	13	41473
VA145E	THY	5000	22689	62	15	21100
VA145H	THY	10000	24692	78	4	3753

**UNIT COST IS THE WEIGHTED AVERAGE OF NEW AND REPAIR COSTS

*FAILURE RATE IS BASED ON THE AVERAGE TIME (YEARS) FOR ALL FAILED TUBES

The tubes were ranked in decreasing order by each of the parameters.

The cost used in the rankings is the weighted average of the new cost and repair cost. It was calculated by the following formula·

$$C = \frac{C_n + \overline{R}C_r}{1 + \overline{R}}$$

C = Cost per operating cycle per tube

Where C_n = new cost

C_r = repair cost

$\overline{R}$ = Average number of times the tube is repaired

$1+\overline{R}$ = Average number of operating cycles per tube

$\overline{R}$ was calculated by a computer program. The formula used was:

$$\overline{R} = \frac{1 \cdot R1 + 2 \cdot R2 + 3 \cdot R3 \ldots\ldots\ldots 10 \cdot R10}{R0 + R1 + R2 + R3 + \ldots\ldots R10}$$

where R0 = number of tubes not repaired (first service cycle)

R1 = number of tubes repaired once

R2 = number of tubes repaired twice

etc.

The failure rate expressed (failures/million hours) is the reciprocal of the mean life multiplied by one million. The mean life calculation included all failures in the data for each tube. Censored data were not included, and infant mortality and wearout failures were included. This gives a rough estimate of the observed failure rate.

Failure rate expressed as (failures/year) refers to the average number of failures per calendar year. It was calculated by taking the reciprocal of the average time (in years) that the tube was installed in the system (i.e. removal date - installation date). This rate is the same as one calculated by multiplying the failure rate in failures/million hours by the operating schedule (Million hours of operation/years installed). This rate refers to failures per calendar year, not per year of continuous operation.

2. Parameters

Cost Per Socket Per Million Hours is the product of failure rate (Failures/ 10^6 hours)and cost per tube. This indicates the cost of continuous operation of an installation with one socket. Depending on reliability and cost, it may be better to have more reliable tubes that cost more than less reliable tubes that cost less. There is a non-linear relationship between cost and reliability, so the tendency is for higher reliability tubes to come out cheaper because fewer are needed. Cost per socket per million hours is strictly a measure of the cost-reliability relationship for a tube and not an indication of overall expenditures.

Total Cost Per Million Hours is the product of failure rate (Failures/10^6 hours), cost per tube and number of installations. This is the total cost of continuous operation for all installations in the field using the tube. The ranking changes somewhat from the previous ranking, because the cost per socket per million hours is multiplied by the number of installations. Power is not accounted for in this parameter, so it is only an indication of economic desirability of the tube. This parameter is useful from an expenditure-reliability point of view.

Cost Per Socket Per Million Hours Per KW is the failure rate (Failures/10^6 hours) times cost per tube divided by average power. The power is included because the high power tubes generally cost more than the low power tubes, which tends to bias the ranking. Dividing by power corrects for this bias. This is therefore a good measure of merit from the cost-reliability-capability standpoint for a tube. Tubes with the worst reliability and highest cost tend to be at the top of the list.

Total Cost Per Million Hours Per KW is the failure rate (Failures/10^6 hours) times cost per tube times the number of installations divided by the average power.

This is the total cost per kilowatt of all installations in the field using this tube.

Cost Per Socket Per Year is the failure rate (Failures/year) times unit cost. Failure rate by calendar year incorporates the operating schedule into the cost of using the tube on a fiscal basis.

Cost Per Socket Per KW Per Year is the same as cost per socket per KW per hour except that it includes the operating schedule to obtain annual cost per kilowatt.

Total Cost Per Year is calculated with the average operating schedule, failure rate, number of installations and tube costs. This parameter (total cost per year) indicates tubes for which the largest expenditures are made. The greatest annual savings may be obtained by improving the reliability of these tubes. The question is, "Is investment in research to improve reliability worthwhile?" This is taken to mean, "Will research save money in the long-run?"

The amount of improvement in reliability which results from a given amount of research is not known. In general, an increase in reliability will also increase the tube purchase price. Estimates of the amount of reliabilty improvement and the amount of cost increase expected can be made. A range of values of percent reliability improvement and percent cost increase were assumed for the following example (Figure VII-1, VII-2).

Economic analysis would need to be performed to determine the amount of money which may be allocated for research for a given increase in reliability and increase in cost. This analysis would include a comparison of the present cost and the projected cost.

Existing cost may be determined by calculating the present worth (PW) of the annual operating costs for, say, a five year period (a five year planning horizon might be chosen because quick payback is desired).

FIGURE VII-1

EXAMPLE OF COST-RELIABILITY CALCULATIONS

TUBE	TUBE COST (C_n)	FAILURES PER YEAR (λ)	SOCKETS	K$/YEAR (S)
L3035	5.49 (K$)	2.4	90	1185.8

PW = 1185.8 (4.23) = 5016

5 years

10% interest

6% inflation

POTENTIAL % FAILURE RATE IMPROVEMENT	POTENTIAL % PRICE INCREASE	(PW) YEARLY OPERATION COST $/YEAR	BREAK EVEN K$
0	0	5016	0
10	5	4736	280
10	10	4967	50
15	5	4475	543
15	10	4691	325
15	15	4091	115
20	10	4415	601
20	15	4612	404
20	20	4817	199

BREAKEVEN = $PW - PW_n$

where PW = present worth of costs using existing price and failure rate

PW_n = present worth of costs using improved failure rate and increased cost.

FIGURE VII-2

EXAMPLE OF COST-RELIABILITY CALCULATIONS

TUBE	TUBE COST (C_n)	FAILURES PER YEAR (λ)	SOCKETS	K$/YEAR (S)
L3403	4.6 (K$)	1.09	74	1178

PW = 1178 (4.23) = 4981

5 years

10% interest

6% inflation

POTENTIAL % FAILURE RATE IMPROVEMENT	POTENTIAL % COST INCREASE	(PW) YEARLY OPERATION COST K$/Year	BREAK EVEN K$
0	0	4981	0
10	5	4707	274
10	10	4927	54
15	5	4446	535
15	10	4675	306
15	15	4888	93
20	10	4384	597
20	15	4572	409
20	20	4771	210

Assuming the cost of money to be 10% per year and the inflation rate to be 6% per year, the calculation is as follows:

$$PW \left(\begin{array}{r} \text{5 years 10\% interest} \\ \text{6\% inflation} \end{array} \right) = S \frac{(1)}{(1+i)} + S \frac{(1+f)}{(1+i)^2} + S \frac{(1+f)^2}{(1+i)^3} + S \frac{(1+f)^3}{(1+i)^4} + S \frac{(1+f)^4}{(1+i)^5}$$

where S = annual cost of tube

i = interest rate (10%)

f = inflation rate (6%)

substituting for i and f above:

$$PW = S(4.23)$$

The present worth for each of the assumed improvements and increases is calculated next.

$$\lambda_n = (1-I)\lambda$$

where λ = original failure rate in $\frac{\text{Failures}}{\text{year}}$

λ_n = new failure rate

I = fractional improvement in failure rate

$$C_n = C\,(1-J)$$

where C = original cost of tube (K\$)

C_n = new cost of tube

J = fractional increase in cost

$$S_n = \text{annual cost} = \lambda_n \times C_n \times N_s$$

where N_s = number of sockets

Therefore, $PW_n = S_n\,(4.23)$ = The cost of operating the improved tube for 5 years assuming 6% inflation and 10% interest.

Ranges of feasible improvement in failure rate and increase in cost should be estimated by personnel familiar with the manufacturing process. Calculations may then be made to investigate the sensitivity of the savings which may result from research. For the final decision on research expenditures, engineering judgement should be used to weigh the possible benefits and consequences.

3. Summary

The tubes were ranked (in decreasing order) by each of the eight parameters. No two have exactly the same order of tubes. This stems from the nature of the parameters.

The ranking by cost per socket per million hours indicates the merit of the individual tubes from a cost effectiveness of reliability standpoint. The ranking order changes, however, when total cost per hour is considered. This is due to the different number of sockets in the field for the different tube types. The total cost is not as significant from a reliability standpoint; however, it is important to the economist, who wants to minimize total cost.

The cost/socket/KW/hour is important from an efficiency standpoint. Low power tubes have lower cost, but not necessarily in proportion to the power. Applying the number of sockets to get the total cost again changes the order of ranking.

C. UTILITY

If the operating schedule is constant, total cost per year seems to be the most significant parameter. The largest expected cost reduction would result from improving the reliability of the tubes ranked in descending order by this parameter.

The range of improvement possible should be estimated for each tube. The cost associated with each improvement must also be estimated. Using these estimates, economic analyses should be performed to determine if research is worthwhile, and how much can be spent for research to achieve the improvement.

Rankings by other parameters are included and may be helpful for planning purposes. If operating schedule changes are anticipated, the ranking by cost per socket should be consulted. Where possible, the operating schedule should increase usage of tubes low on the list and decrease usage of tubes high on the list. If power requirements are subject to change, the ranking by cost per socket per kilowatt should be used. This ranking indicates the tubes which are most cost effective in terms of power. The ranking by cost per socket per hour is an indication of the relative merits of the tubes with respect to reliability.

Cost of changes may be estimated by calculating the new failure rate in (failures/year). This may be done by multiplying the failure rate by the projected operating schedule. Using the new failure rate, the cost of the project change may be compared with the existing cost.

The decision to invest in research on reliability improvement should be based on the potential payoff of the research. In each case the best estimates of potential improvement available should be used to determine the possible payoff.

VIII REFERENCES

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3. Mann, Nancy R., Ray E. Shafer and Nozer D. Singpurwalla, Methods for Statistical Analysis of Reliability and Life Data, John Wiley & Sons, New York, 1974.

4. Mann, Nancy R. and Kenneth W. Fertig, "A Goodness-of-Fit Test for the Two Parameter vs. Three Parameter Weibull; Confidence Bounds for Threshold", Technometrics, Vol. 17, No. 2, May, 1975.

5. Federal Aviation Administration, "Federal Aviation Administration Specification, Airport Surveillance Radar (ASR) Transmitter-Receiver (T/R) Subsystem", FAA E-2506 Amendment-3, Department of Transportation, August 1973.

APPENDIX

This appendix contains reliability function plots for the tubes studied during the program. Each curve is a plot of the following reliability function:

$$R(t) = e^{-\lambda t}$$

where t = time

λ = failure rate

List of Figures

FIGURE A-1 3KM300LA KLYSTRON RELIABILITY, R(t)

(λ = 64)

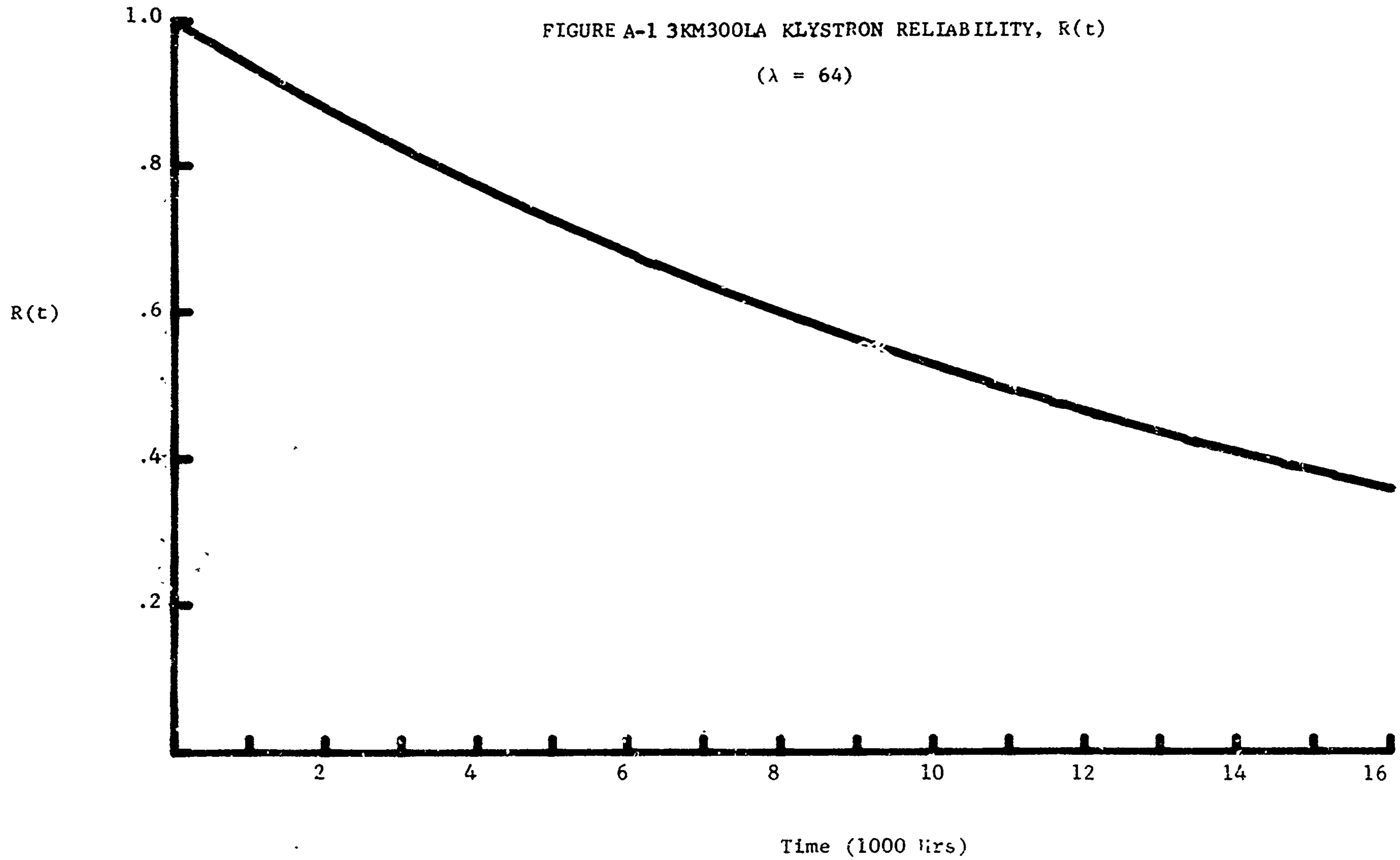


FIGURE A-2 3K210000LQ KLYSTRON RELIABILITY, R(t)

(λ = 151)

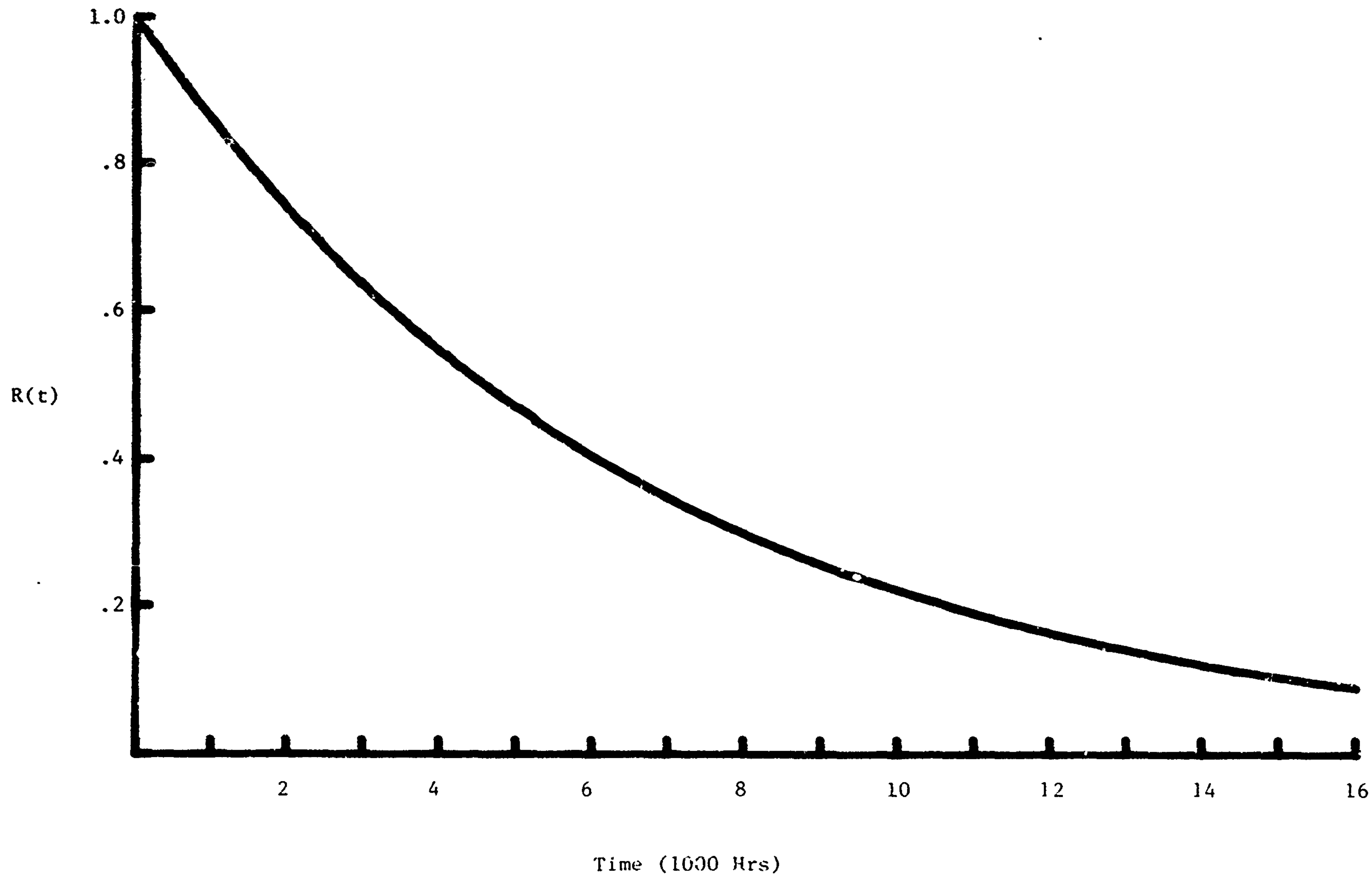
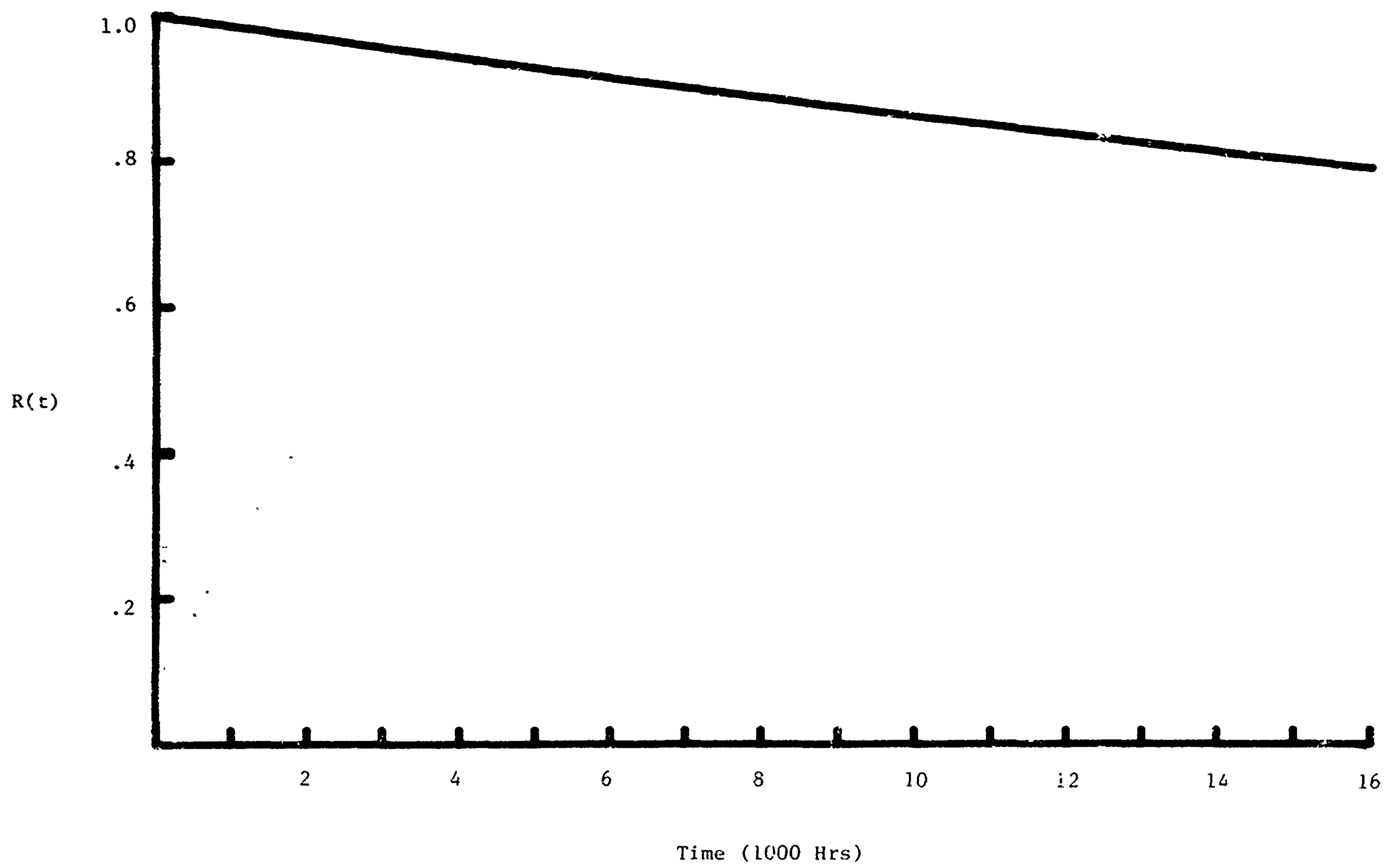


FIGURE A-3 4KM170000LA KLYSTRON RELIABILITY, R(t)

(λ = 15)



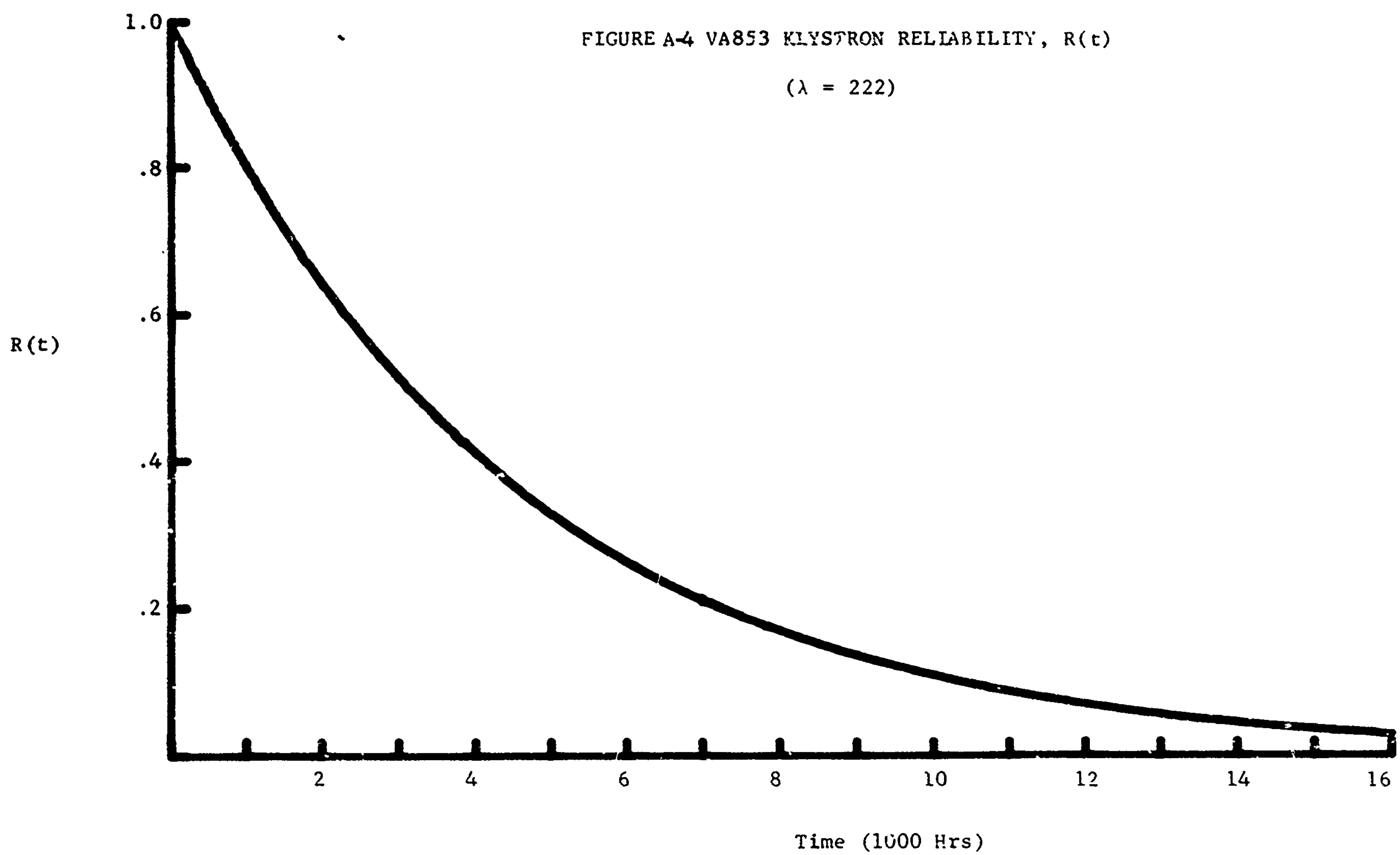


FIGURE A-4 VA853 KLYSTRON RELIABILITY, R(t)

(λ = 222)

FIGURE A-5 8824 KLYSTRON RELIABILITY, R(t)

(λ = 126)

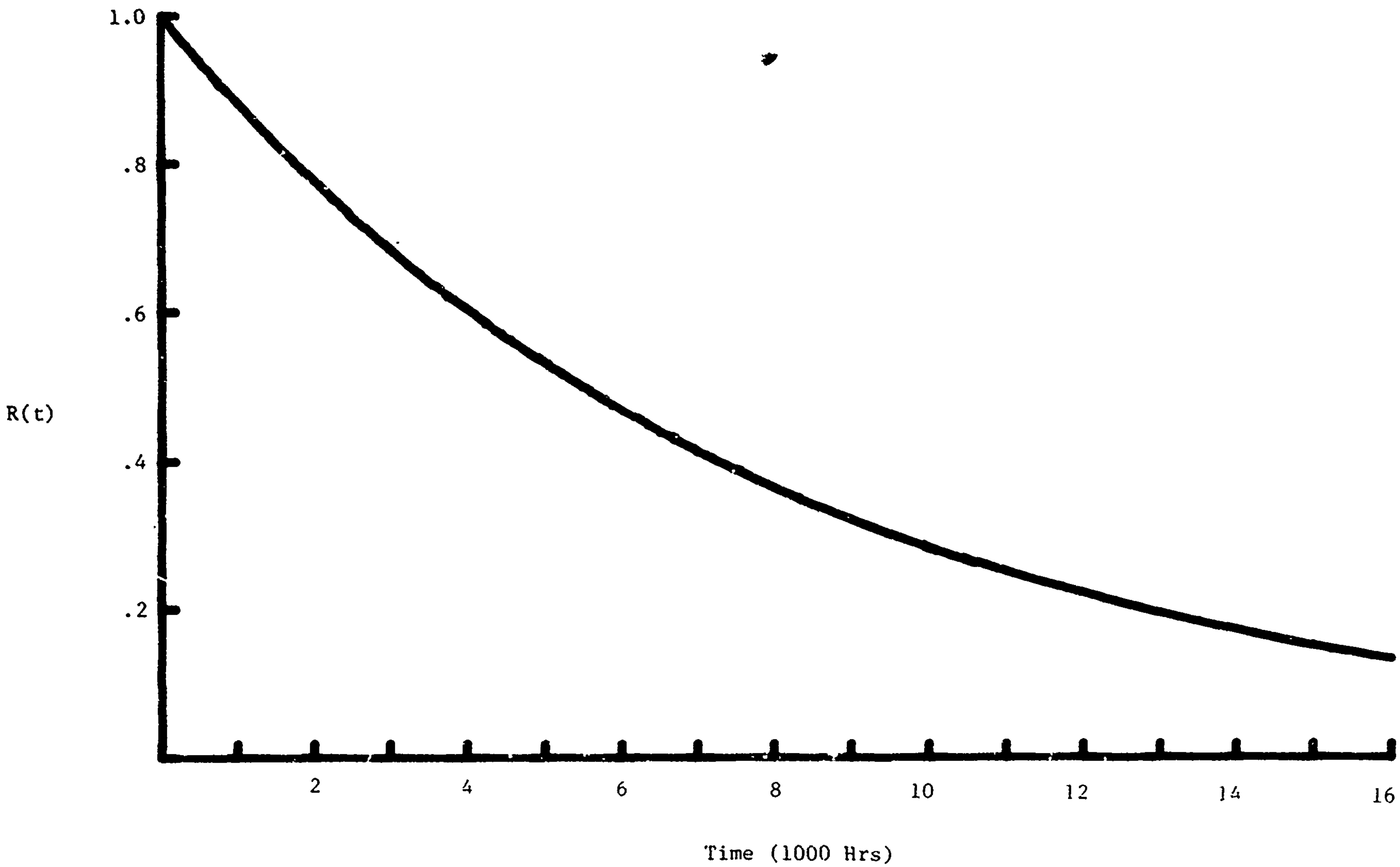


FIGURE A-6 8825 KLYSTRON RELIABILITY, R(t)

(λ = 121)

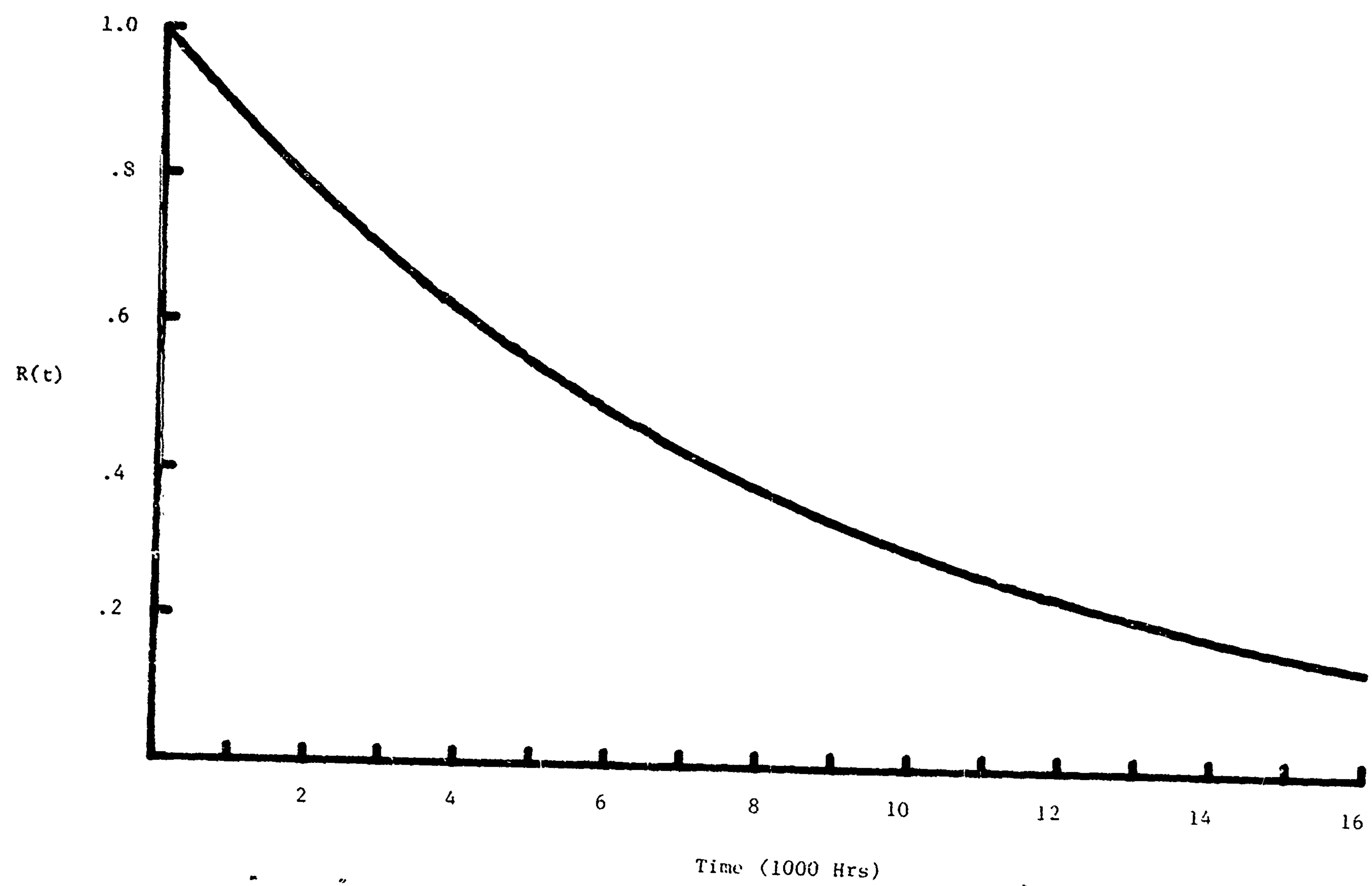


FIGURE A-7 8826 KLYSTRON RELIABILITY, R(t)

(λ = 280)

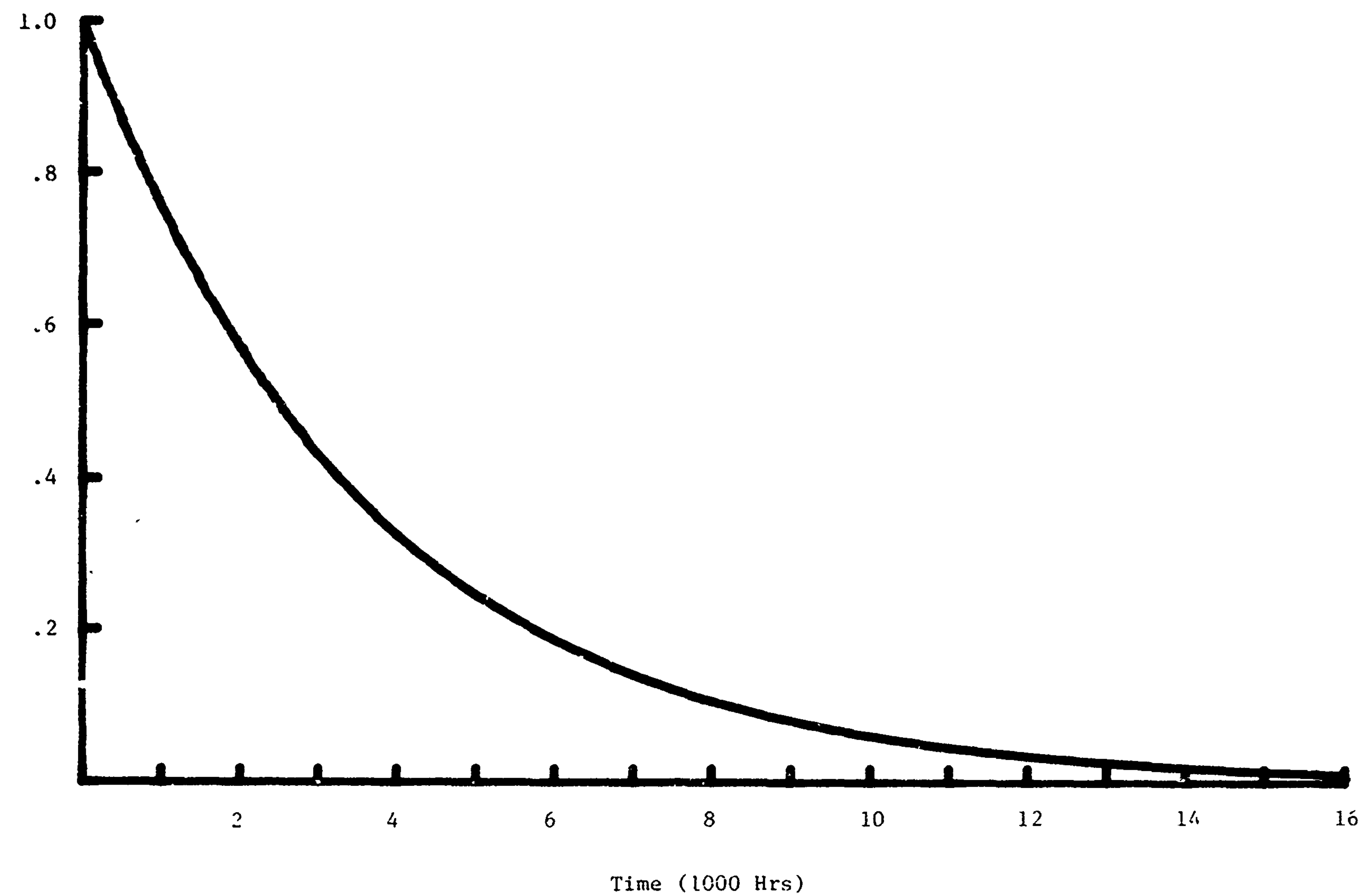


FIGURE A-8 3KM50000PA1 KLYSTRON RELIABILITY, R(t)

(λ = 116)

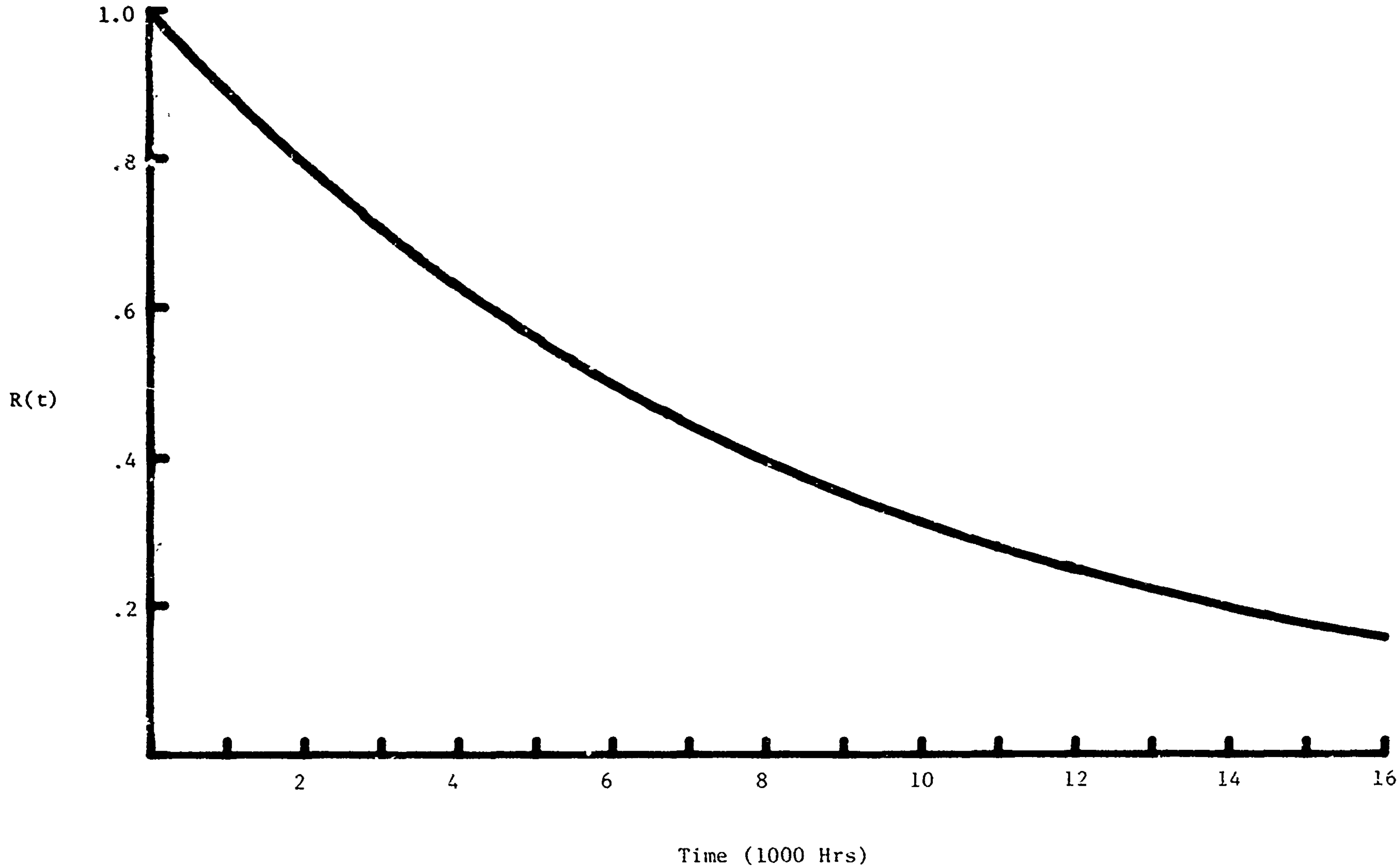


FIGURE A-9 3KM50000PA2 KLYSTRON RELIABILITY, R(t)

(λ = 150)

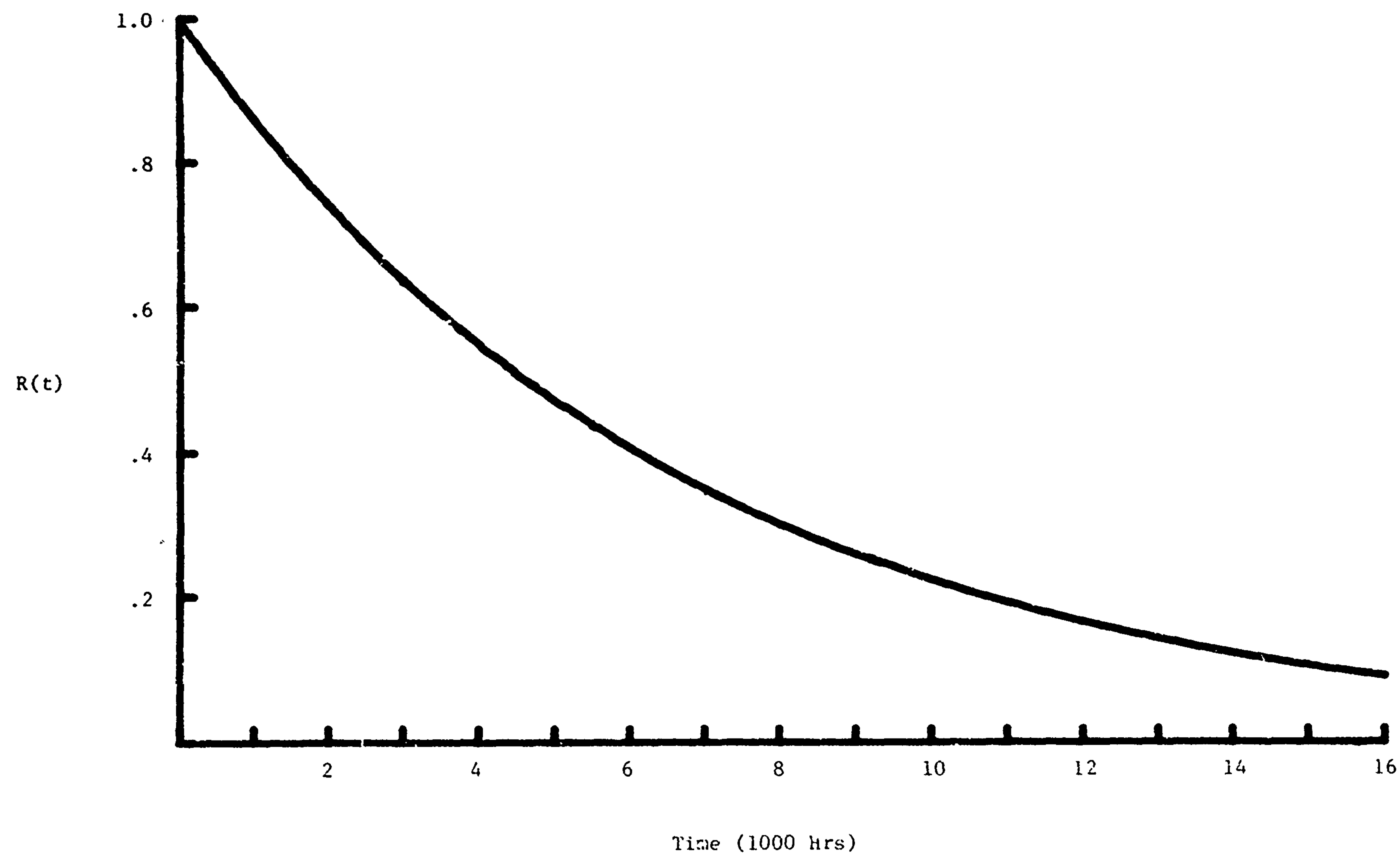


FIGURE A-10 3KM50000PA KLYSTRON RELIABILITY, R(t)

(λ = 111)

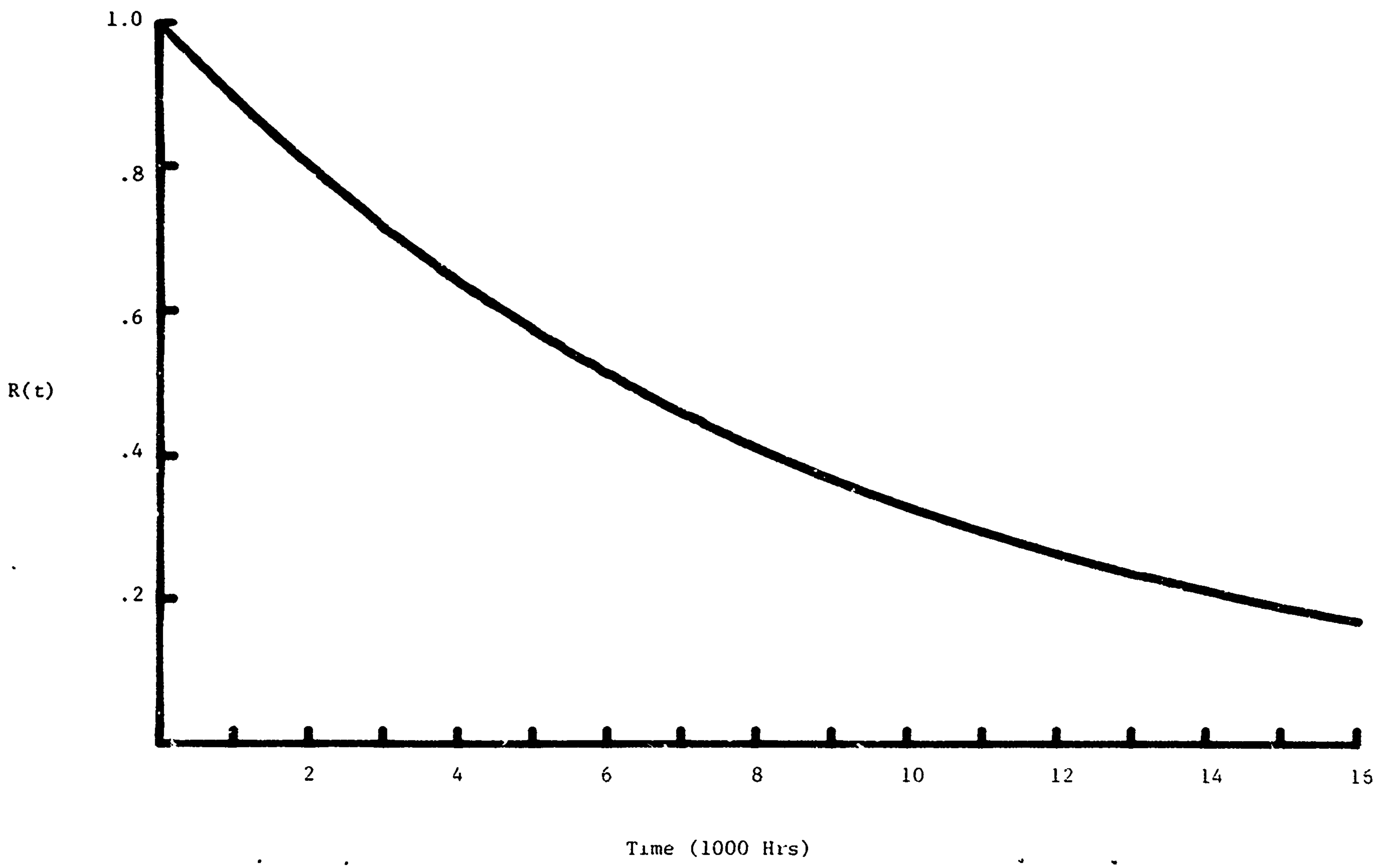


FIGURE A-11 4KM50LB KLYSTRON RELIABILITY, R(t)

(λ = 28)

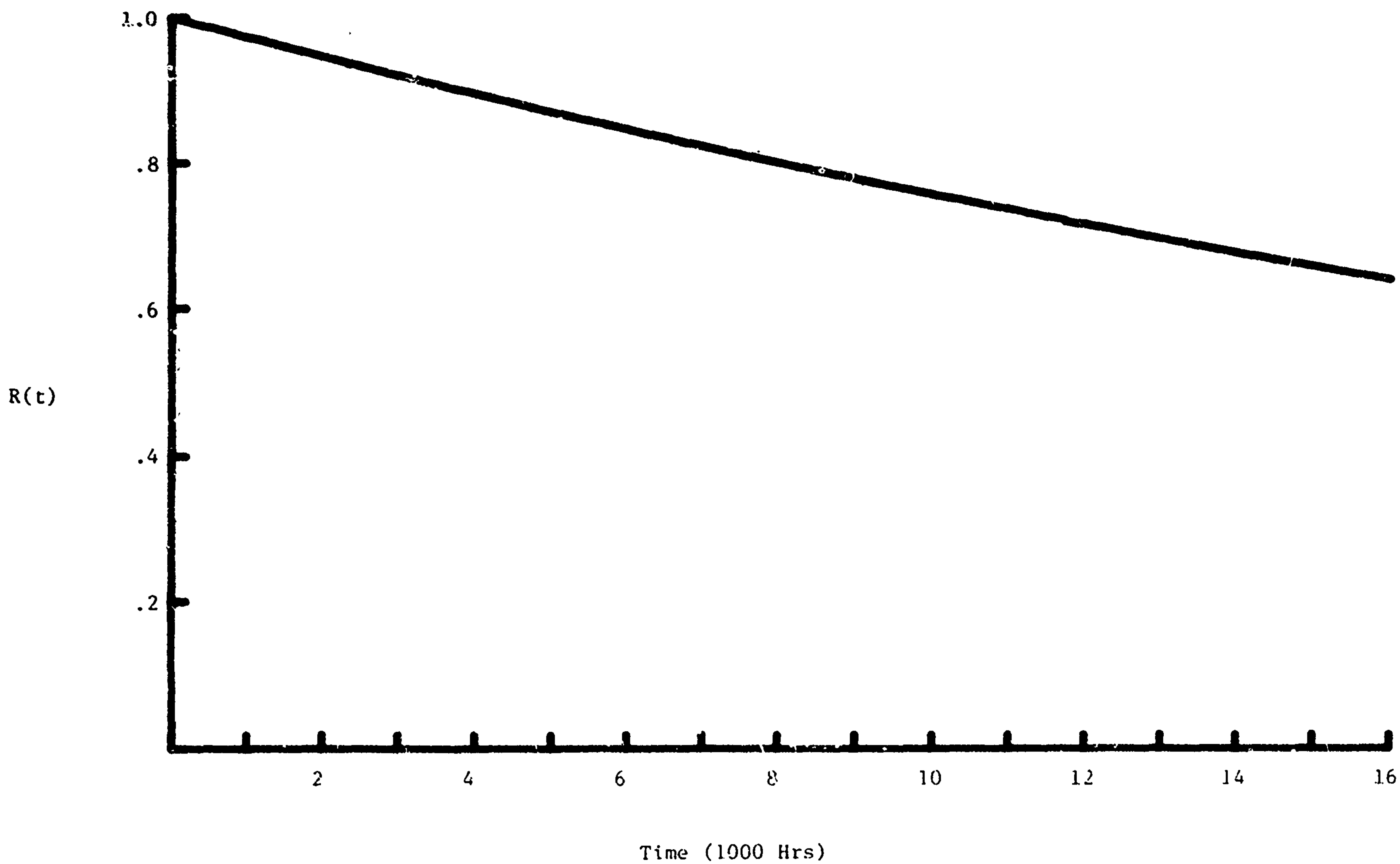


FIGURE A-12 4KM50LC KLYSTRON RELIABILITY, R(t)

(λ = 15)

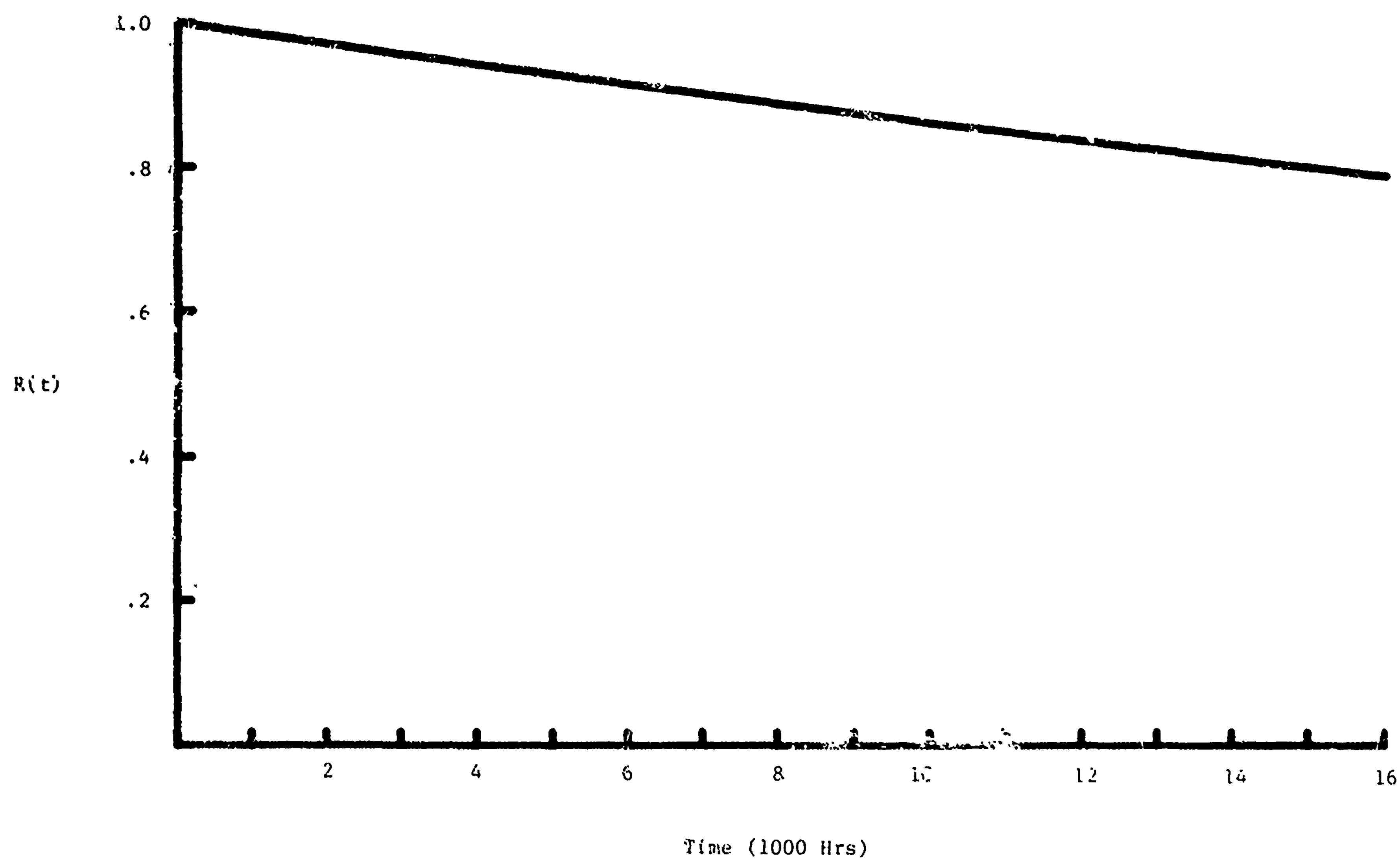


FIGURE A-13 4KM50SK KLYSTRON RELIABILITY, R(t)

(λ = 37)

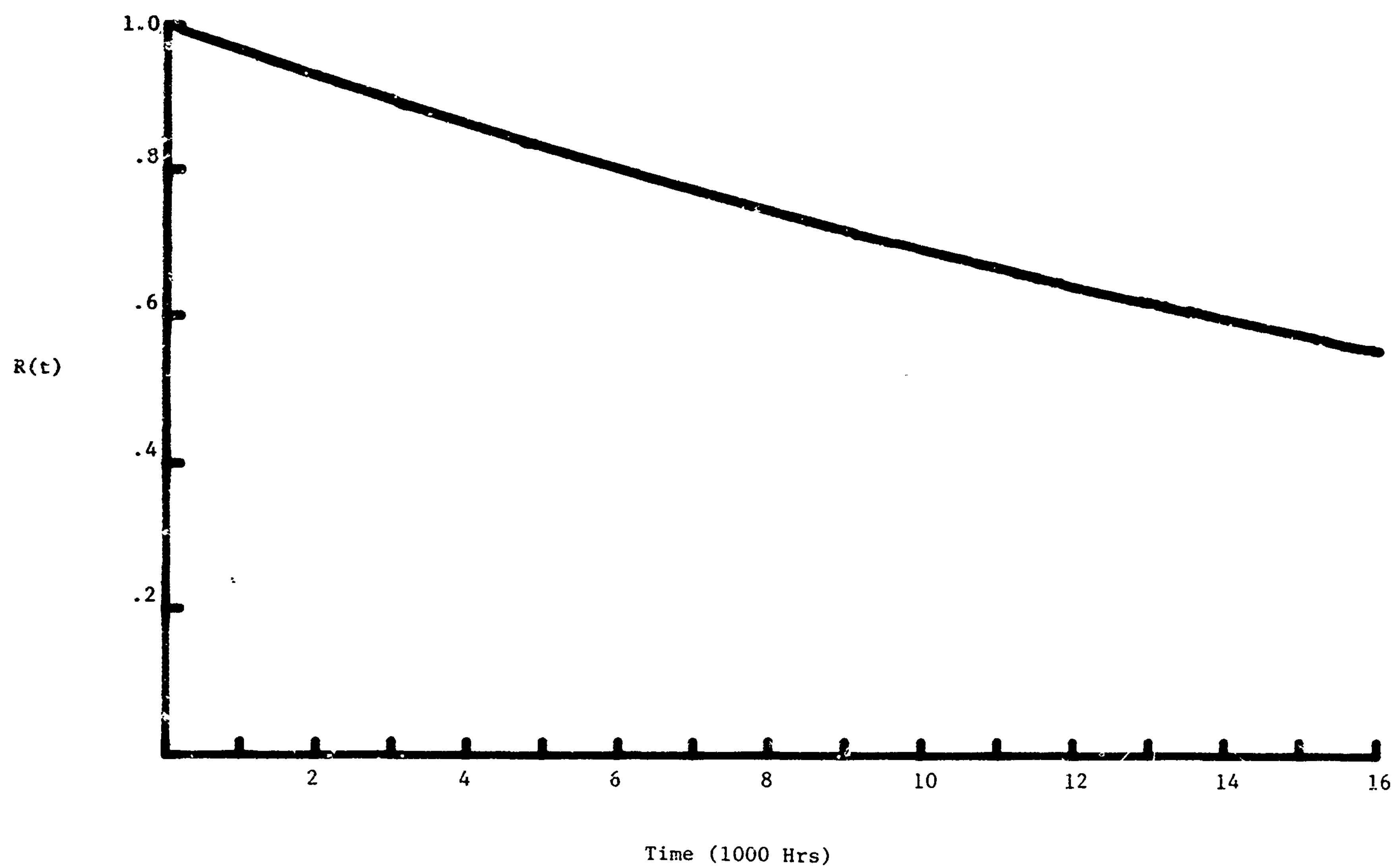


FIGURE A-14 4KM505SJ KLYSTRON RELIABILITY, R(t)

(λ = 38)

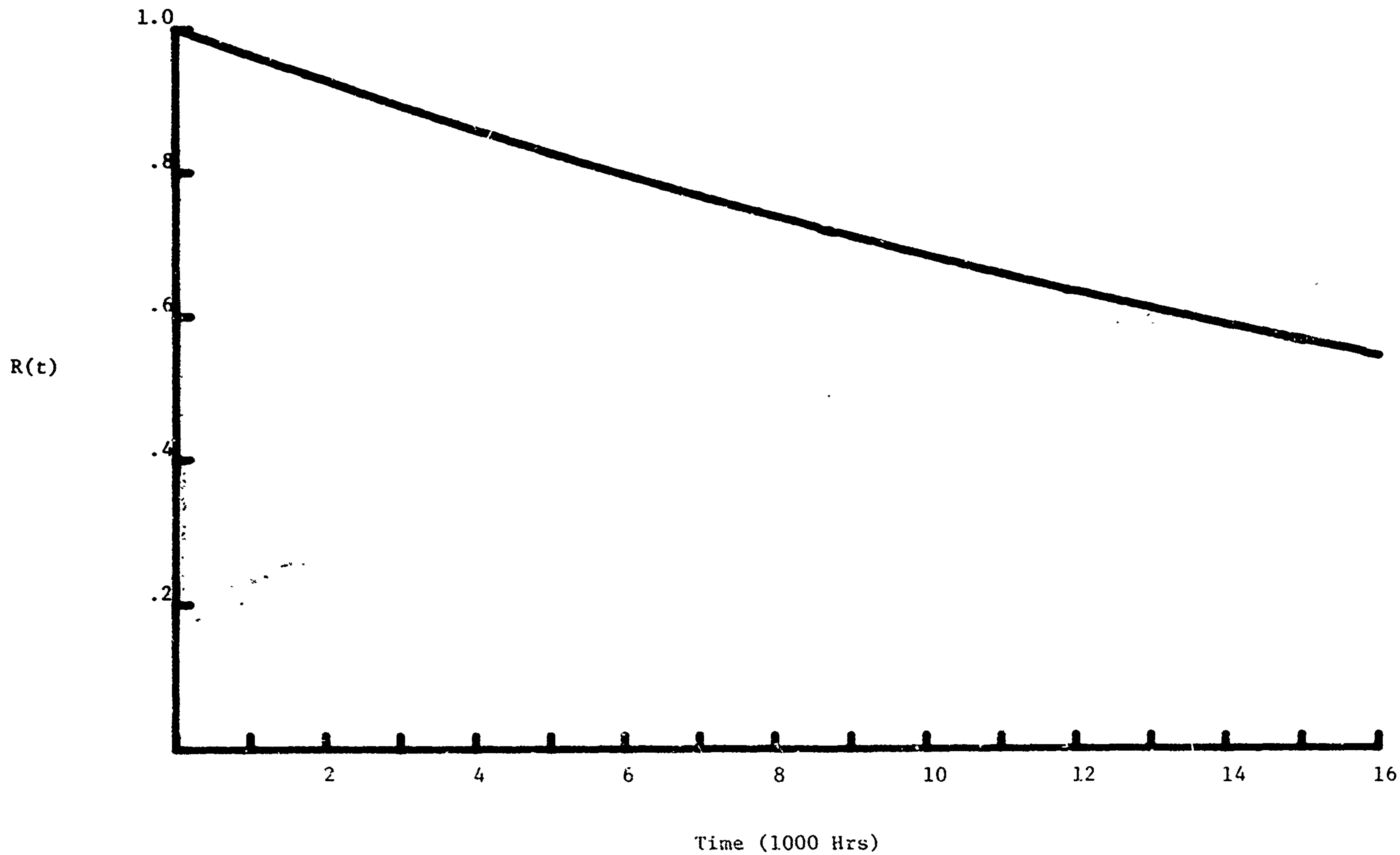


FIGURE A-15 4KM50000LR KLYSTRON RELIABILITY, R(t)

(λ = 57)

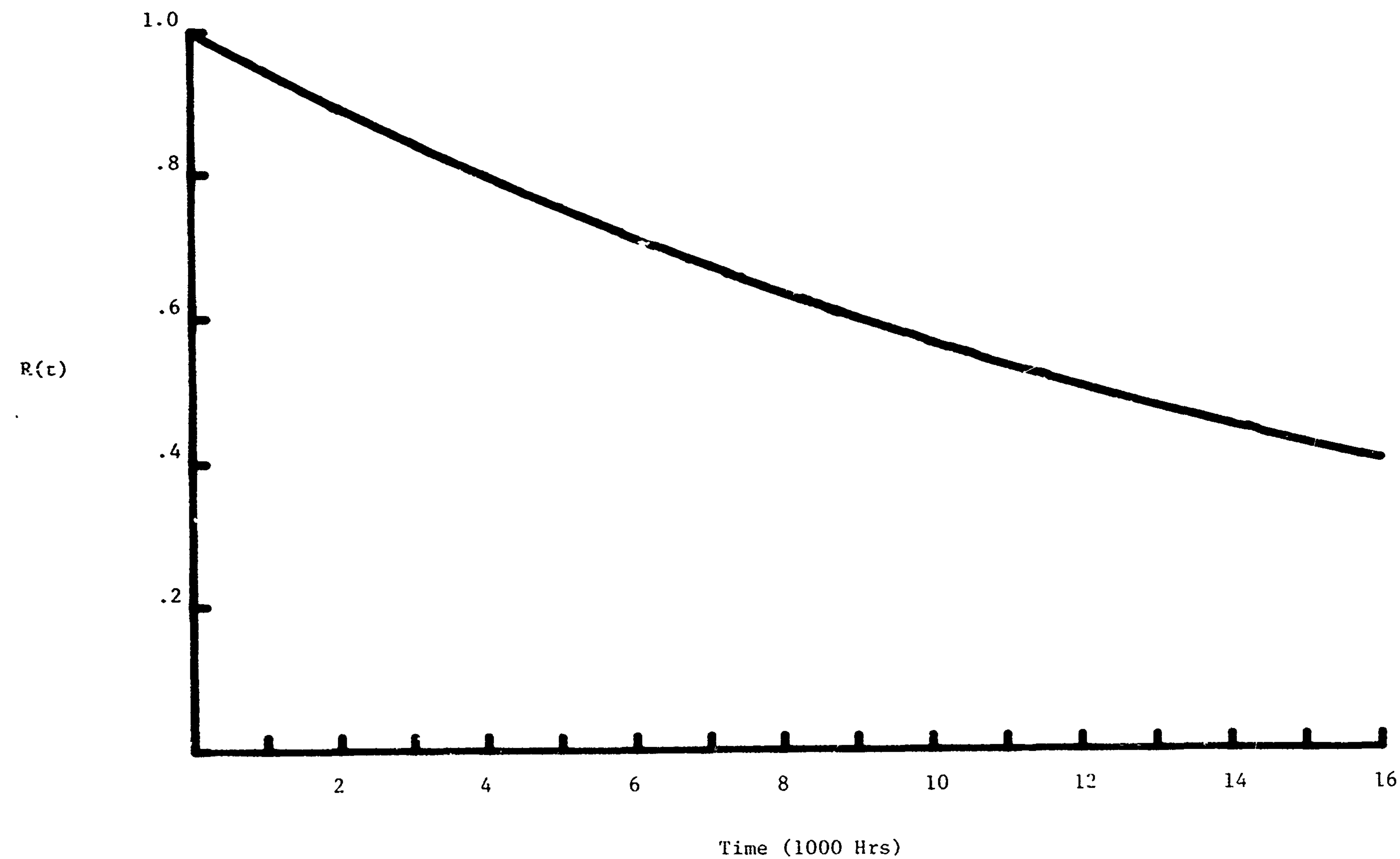


FIGURE A-16 4KM50000LQ KLYSTRON RELIABILITY, R(t)

(λ = 79)

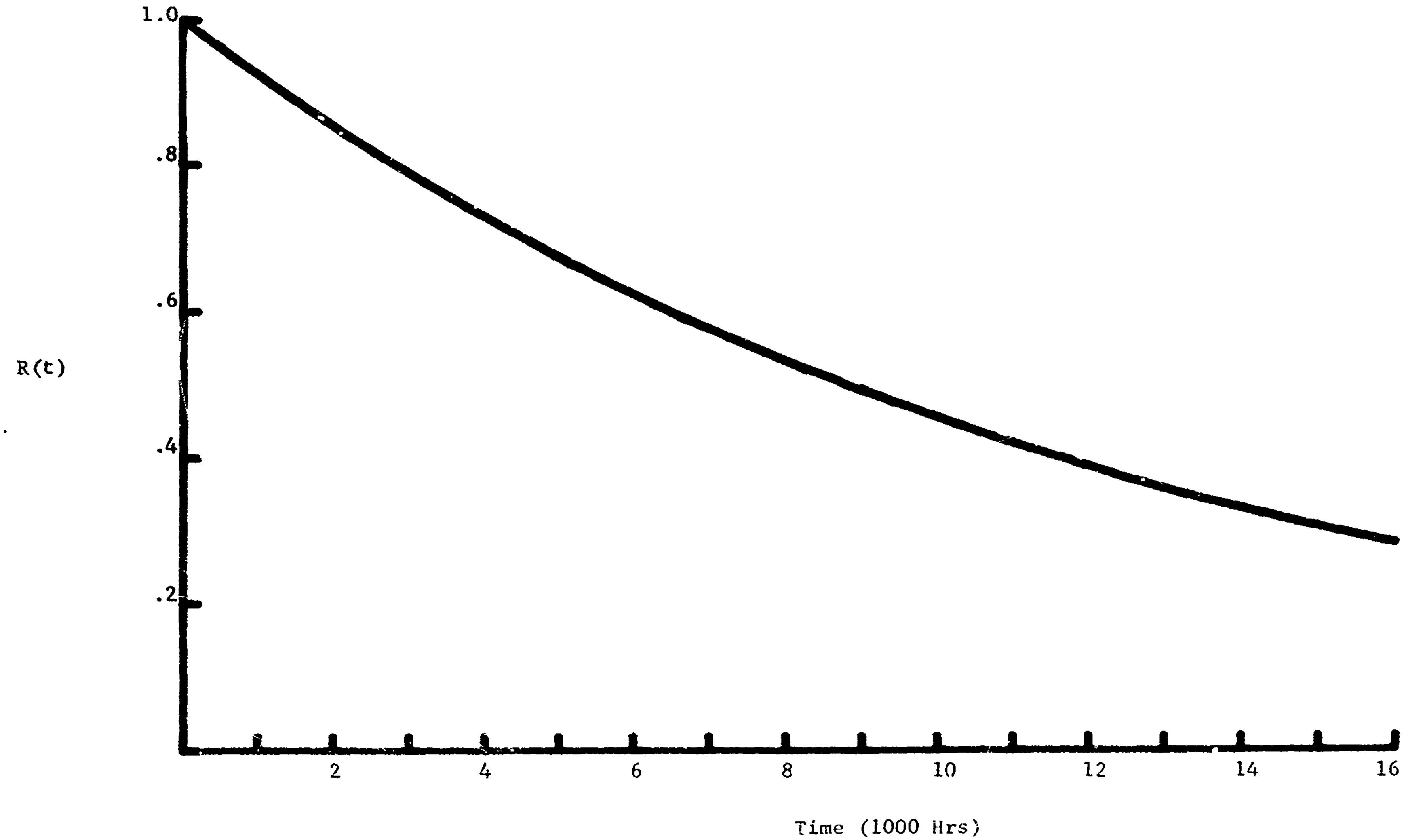


FIGURE A-17 4K50000LQ KLYSTRON RELIABILITY, R(t)

(λ = 30)

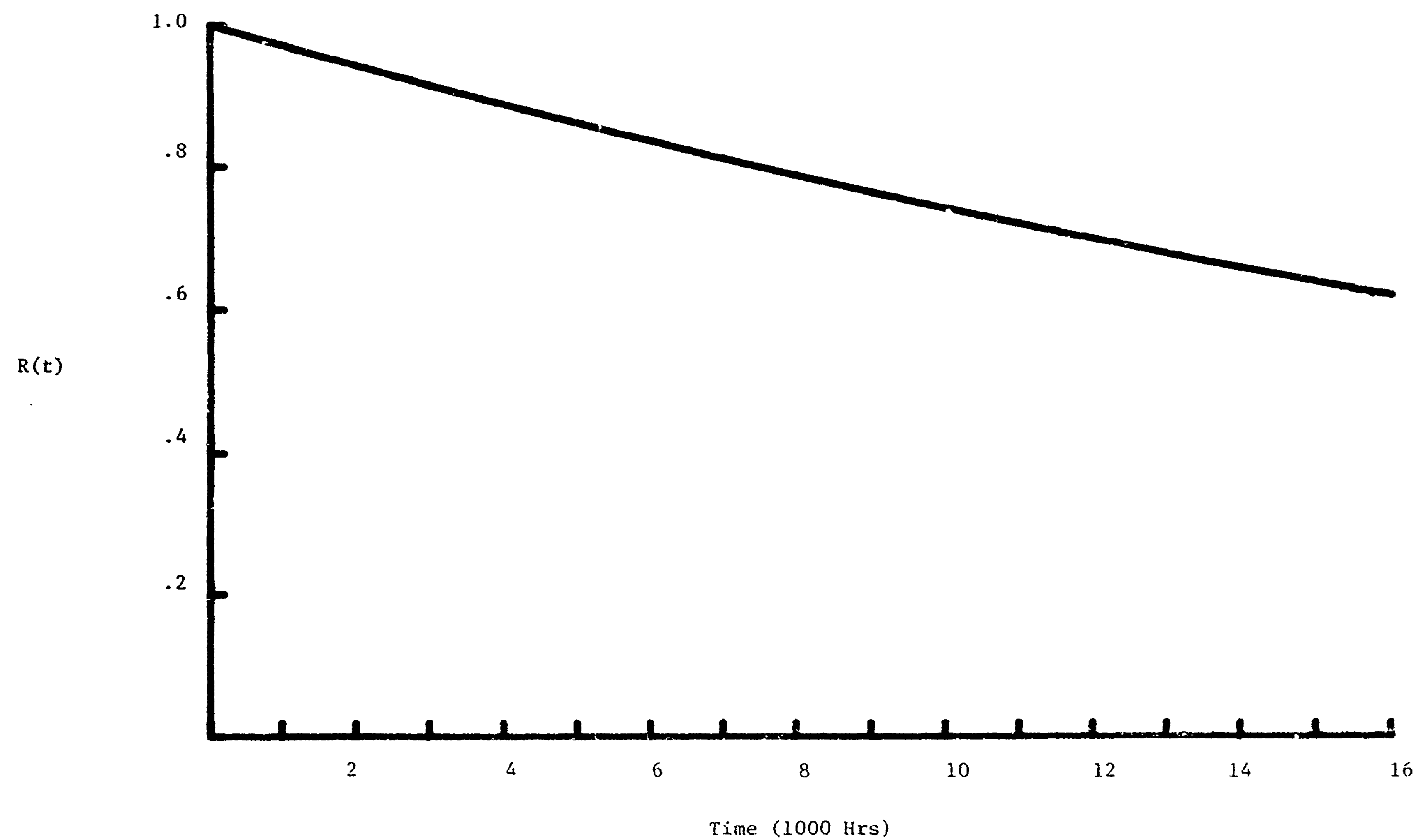


FIGURE A-18 3K50000LA KLYSTRON RELIABILITY, R(t)

(λ = 587)

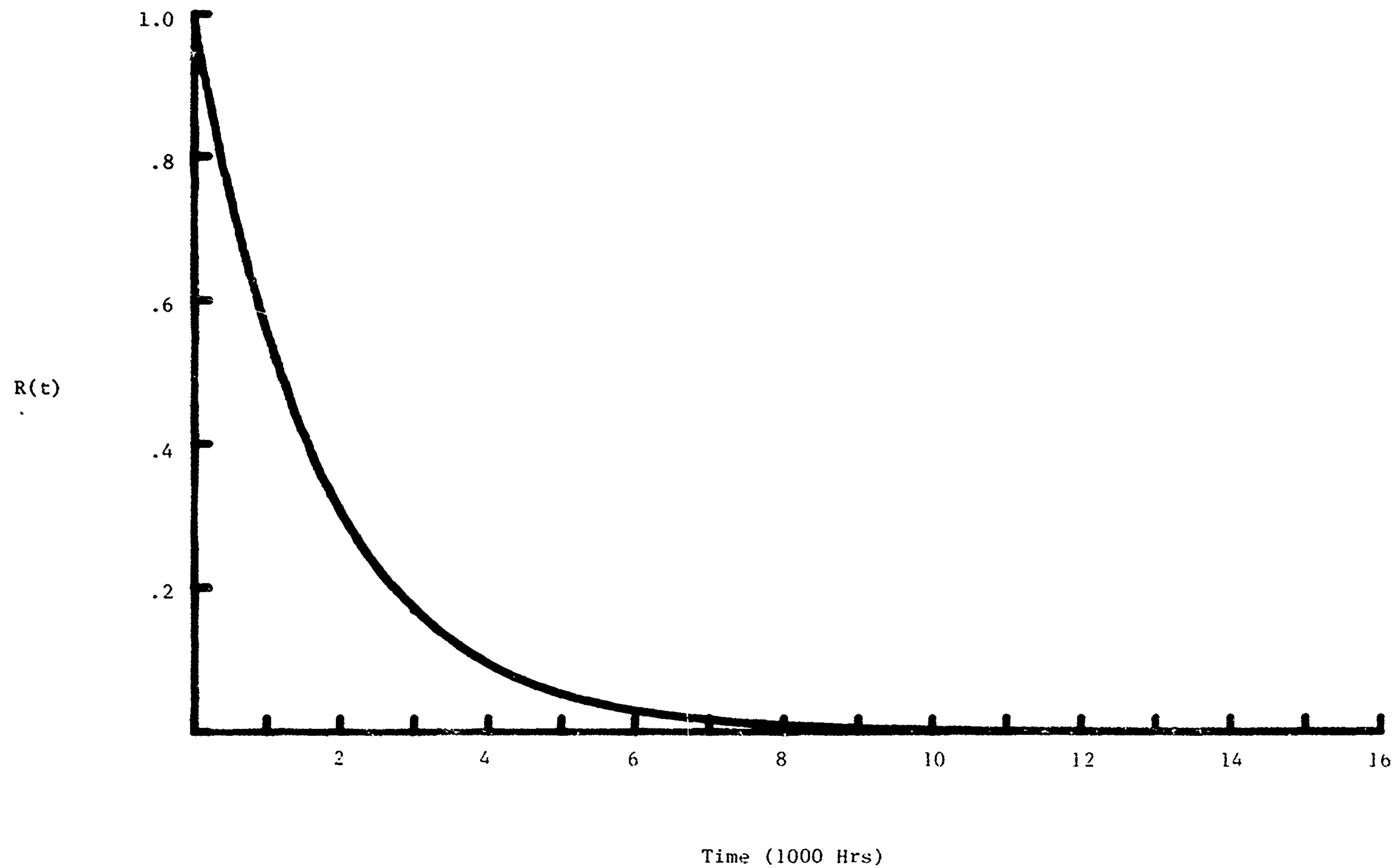


FIGURE A-19 3K50000LF KLYSTRON RELIABILITY, R(t)

(λ = 54)

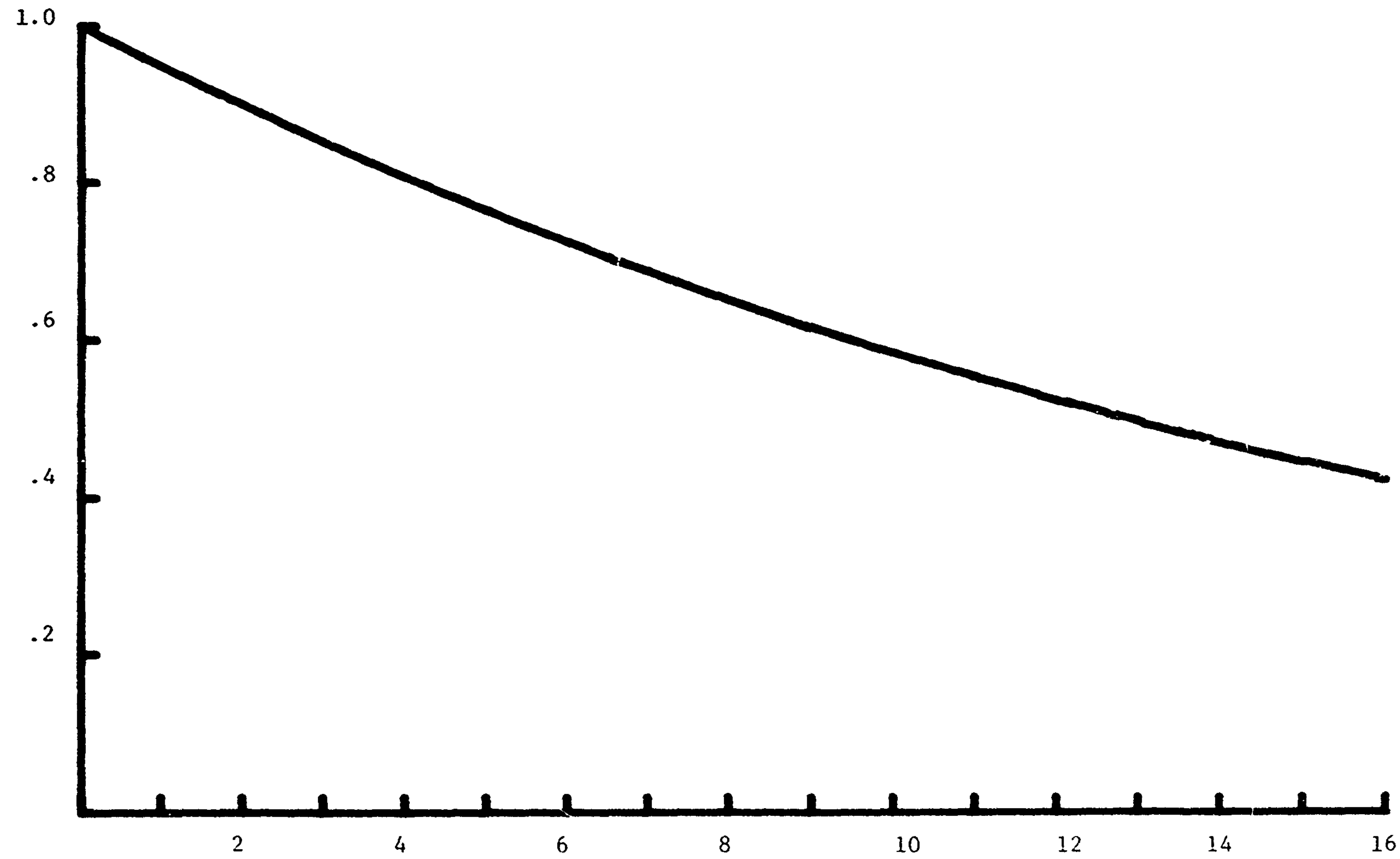


FIGURE A-20 VA800E KLYSTRON RELIABILITY, R(t)

(λ = 70)

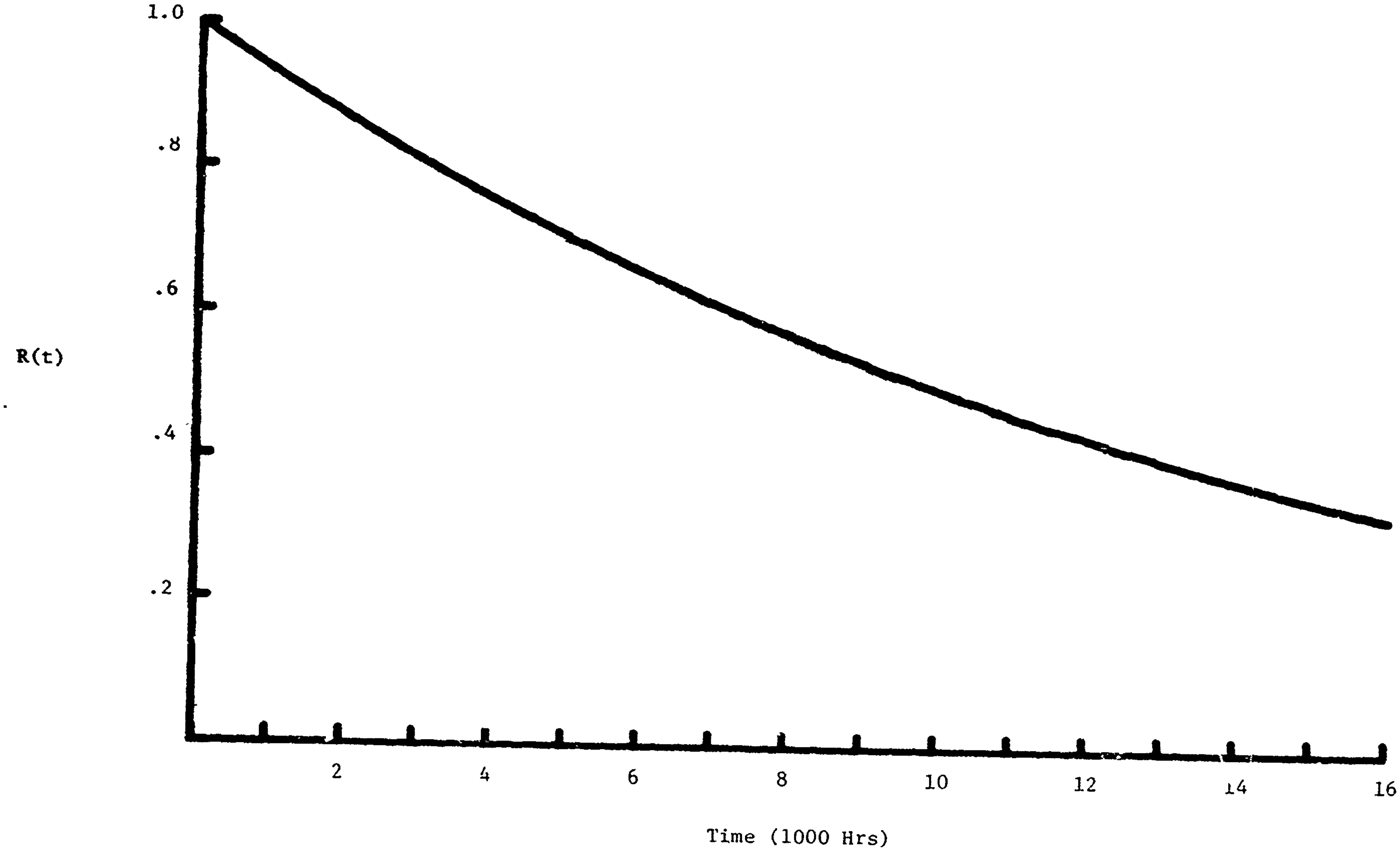


FIGURE A-21 VA856B KLYSTRON RELIABILITY, R(t)

(λ = 65)

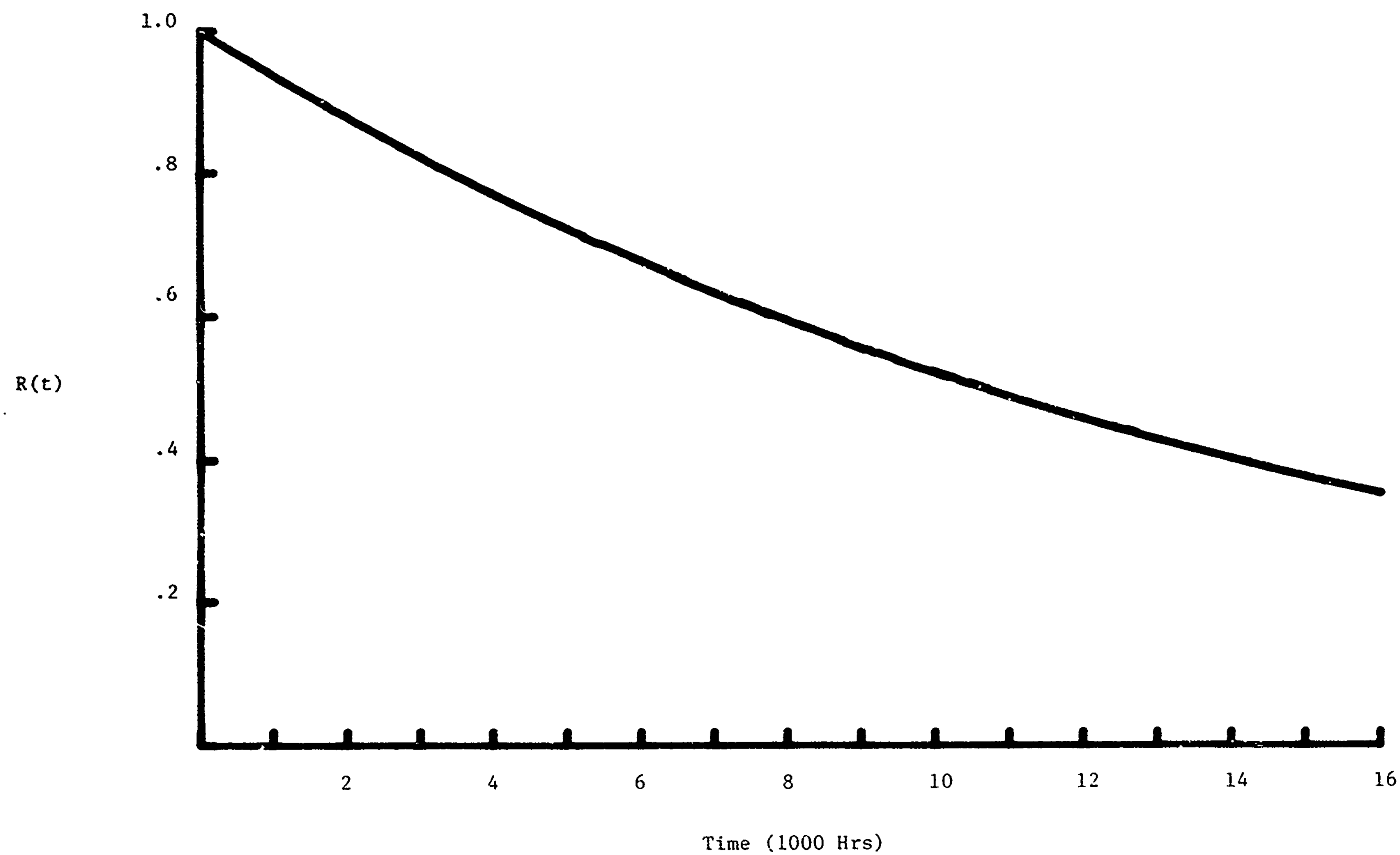


FIGURE A-22 4KM3000LR KLYSTRON RELIABILITY, R(t)

(λ = 138)

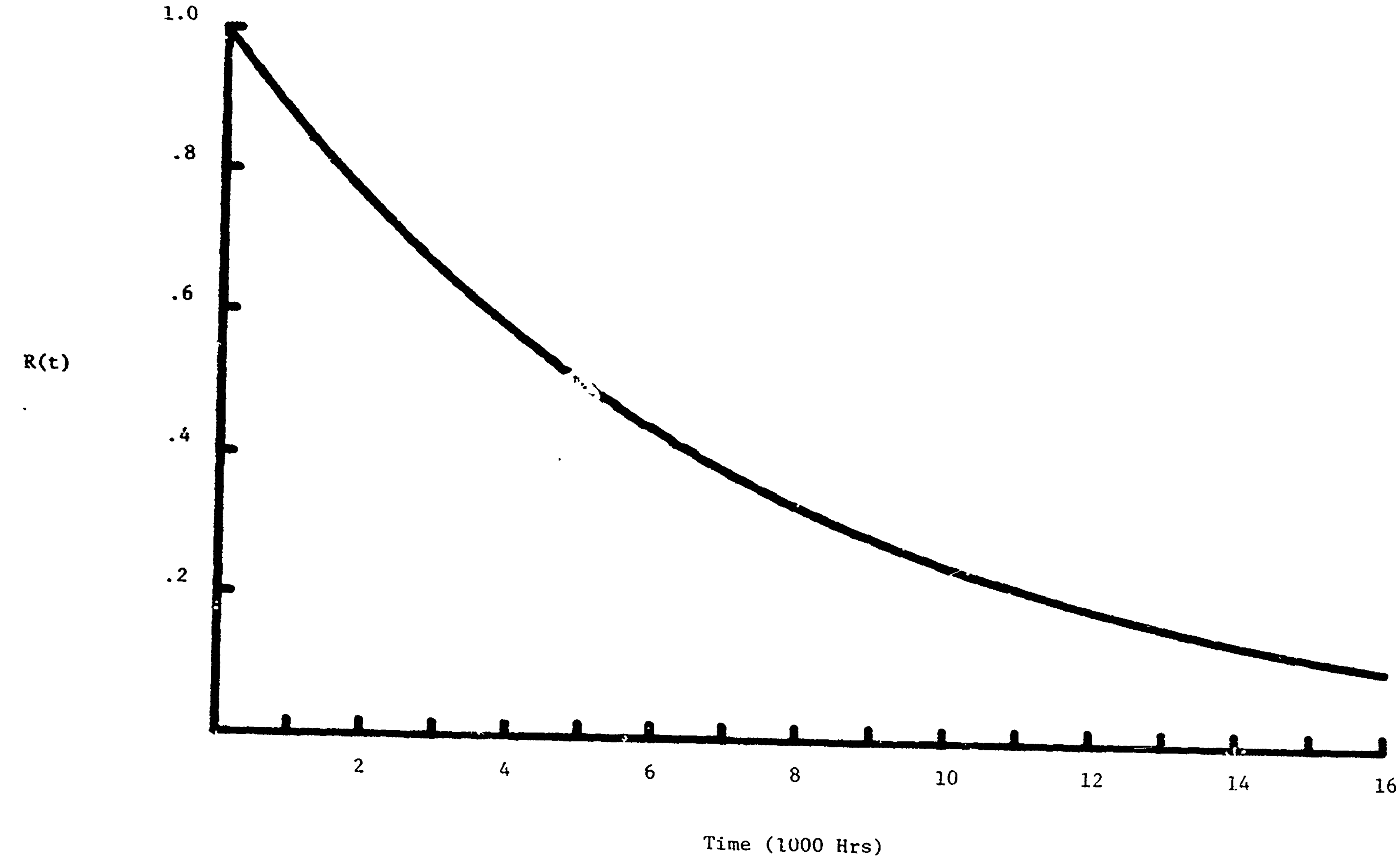


FIGURE A-23 3K3000LQ KLYSTRON RELIABILITY, R(t)

(λ = 9)

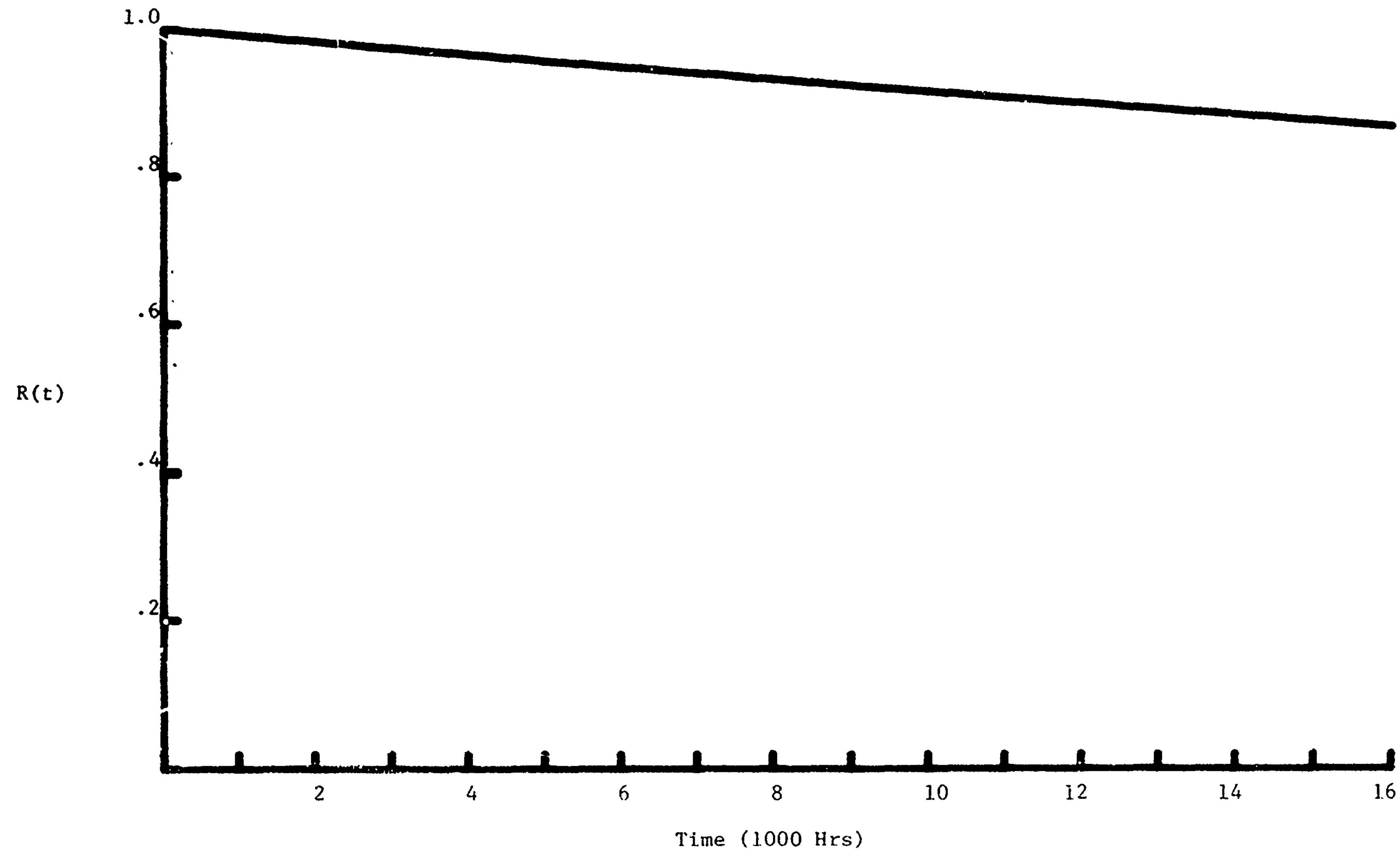


FIGURE A-24 3KM3000LA KLYSTRON RELIABILITY, R(t)

(λ = 19)

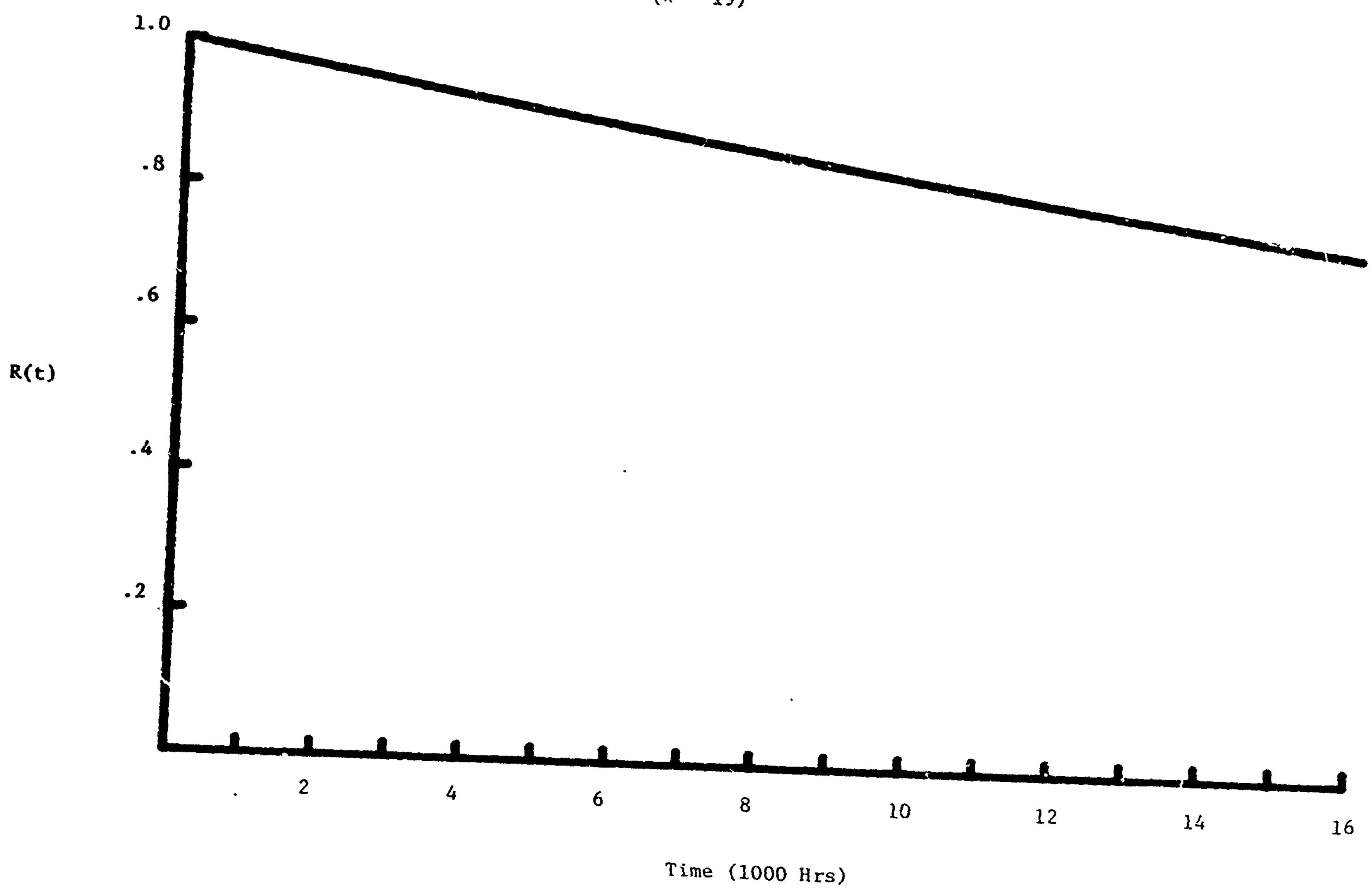


FIGURE A-25 4K3CC KLYSTRON RELIABILITY, R(t)

(λ = 605)

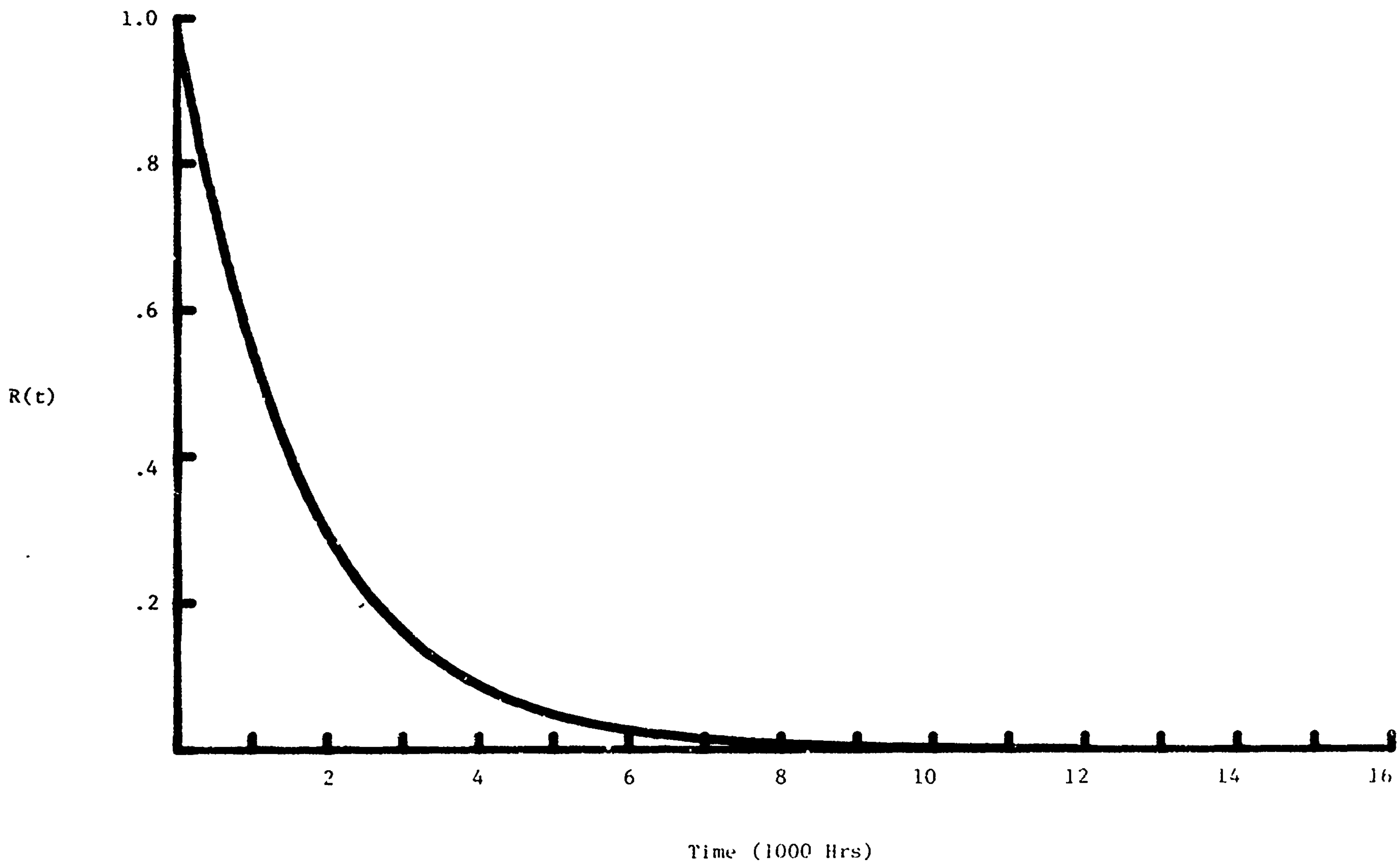


FIGURE A-26 VA888E KLYSTRON RELIABILITY, R(t)

(λ = 233)

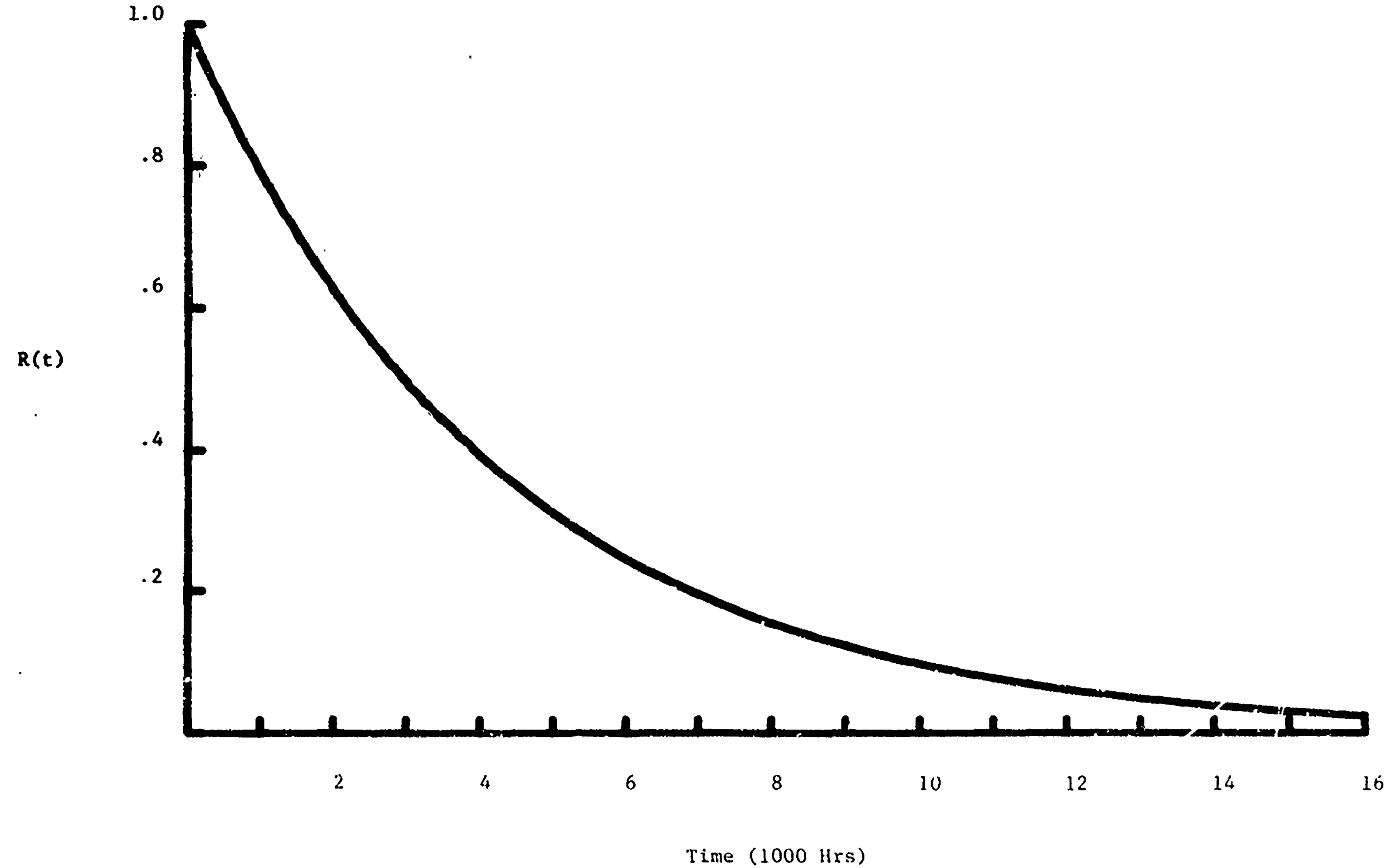


FIGURE A-27 4K3SK KLYSTRON RELIABILITY, R(t)

(λ = 29)

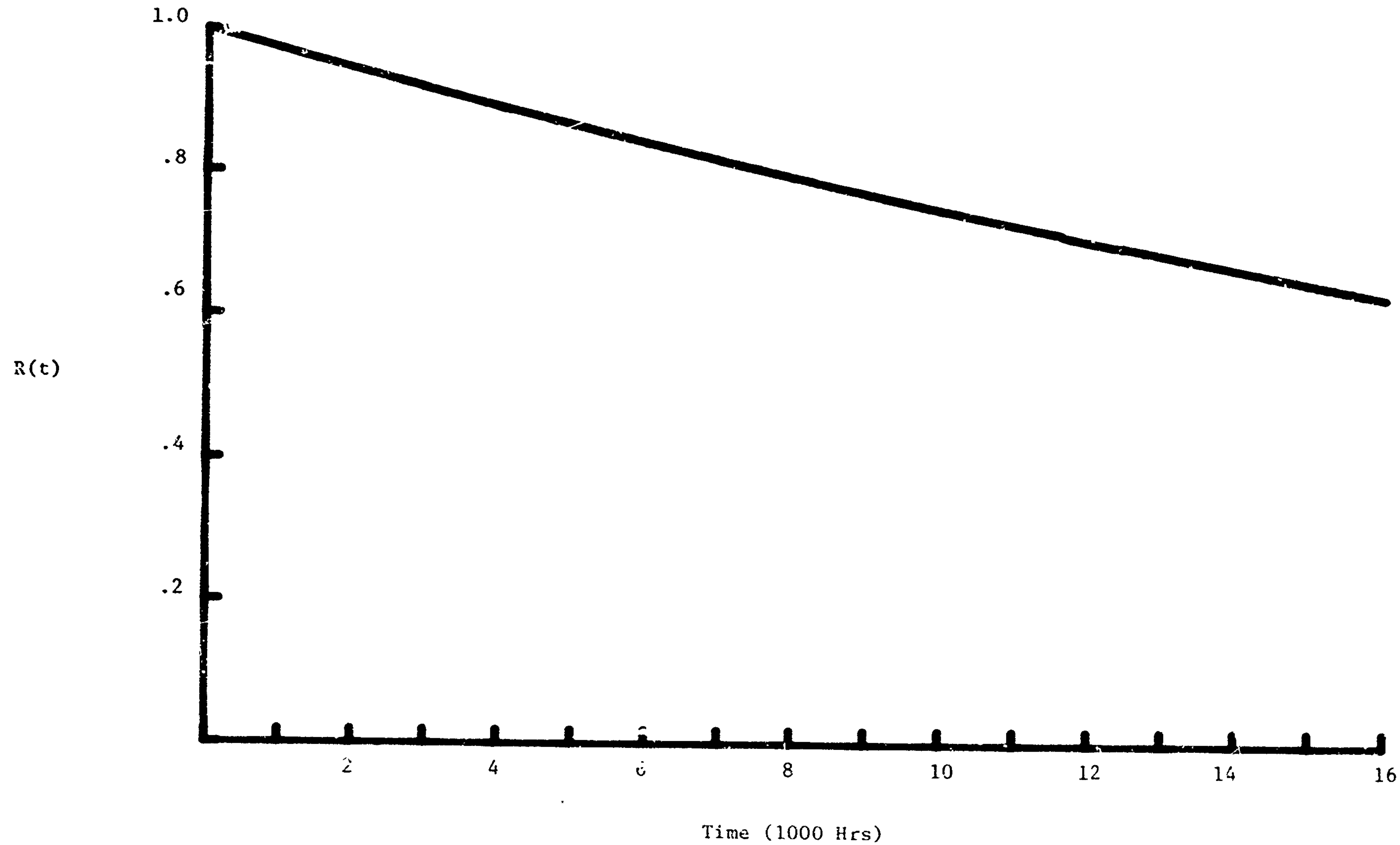


FIGURE A-28 4670 KLYSTRON RELIABILITY, R(t)

(λ = 39)

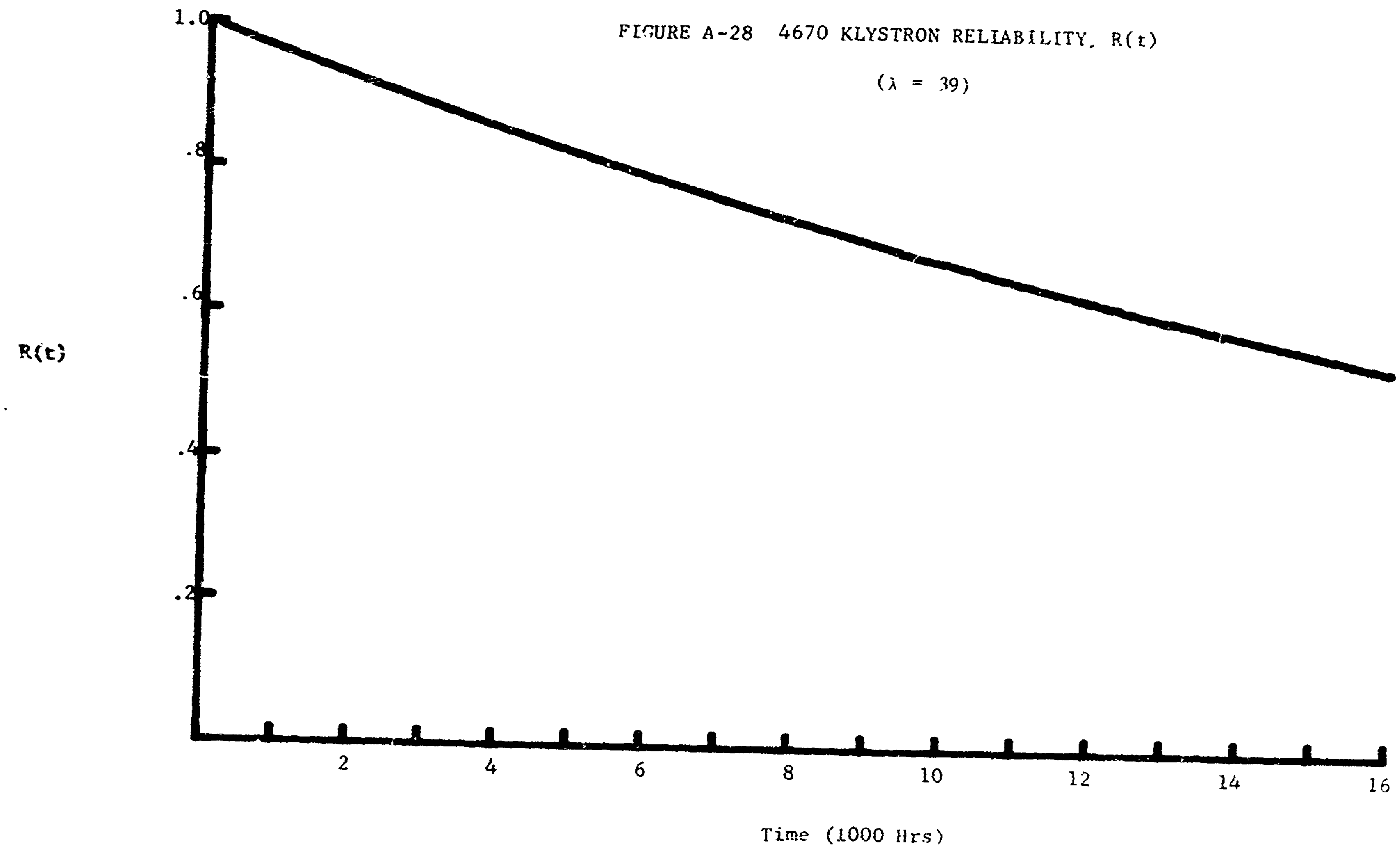
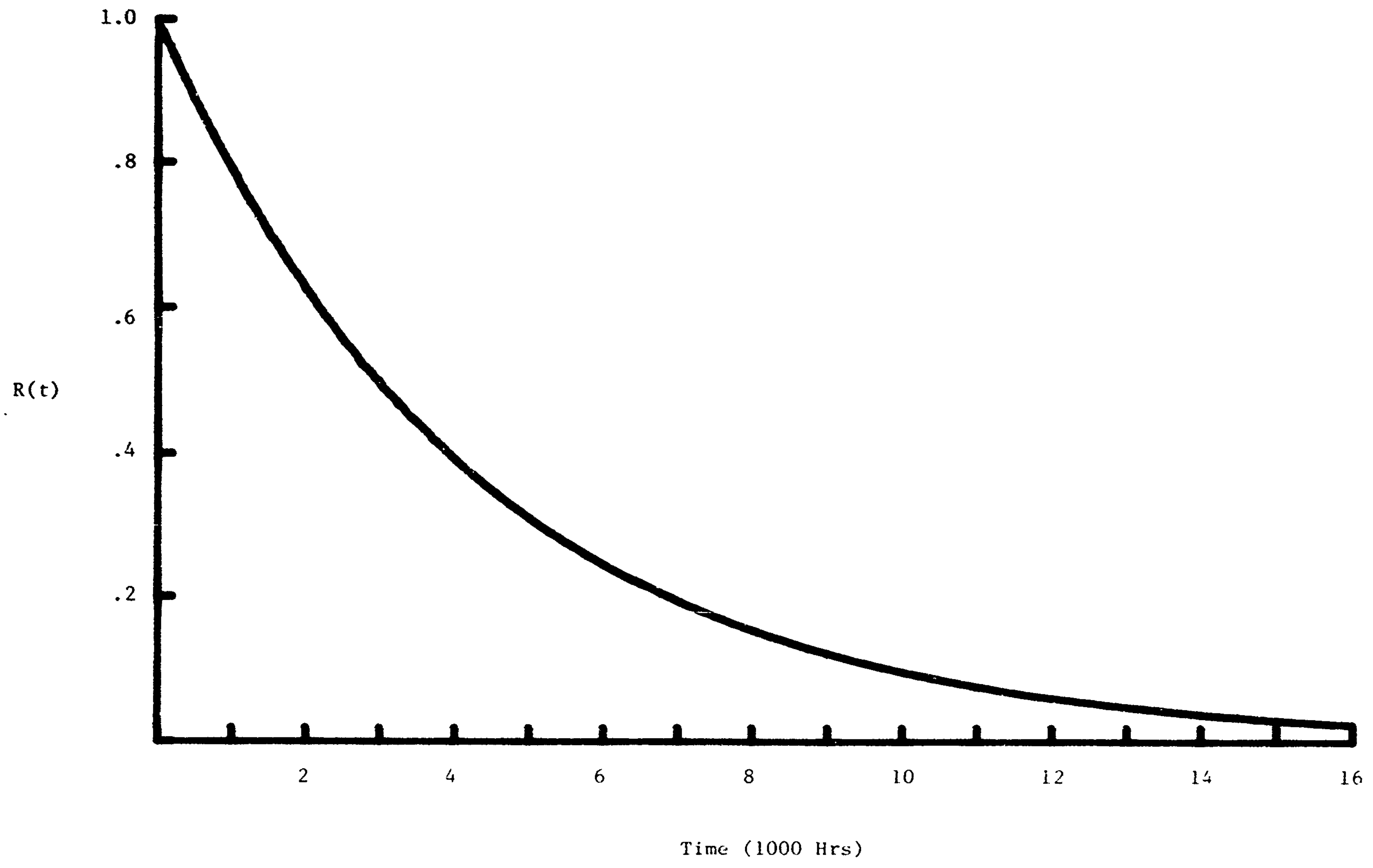


FIGURE A-29 8568 KLYSTRON RELIABILITY, R(t)

([illegible] = 234)



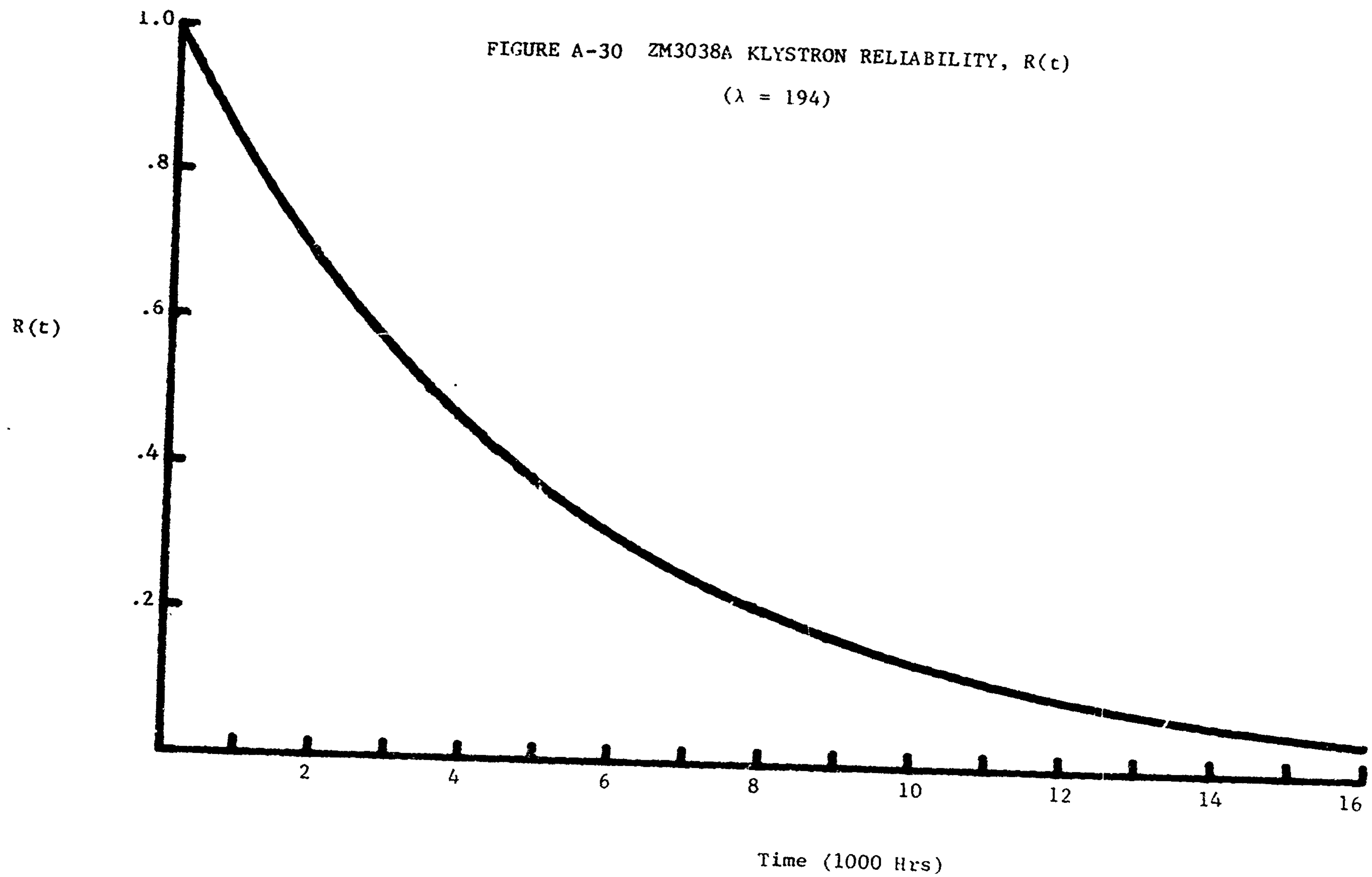


FIGURE A-30 ZM3038A KLYSTRON RELIABILITY, R(t)

(λ = 194)

FIGURE A-31 L3250 KLYSTRON RELIABILITY, R(t)

(λ = 69)

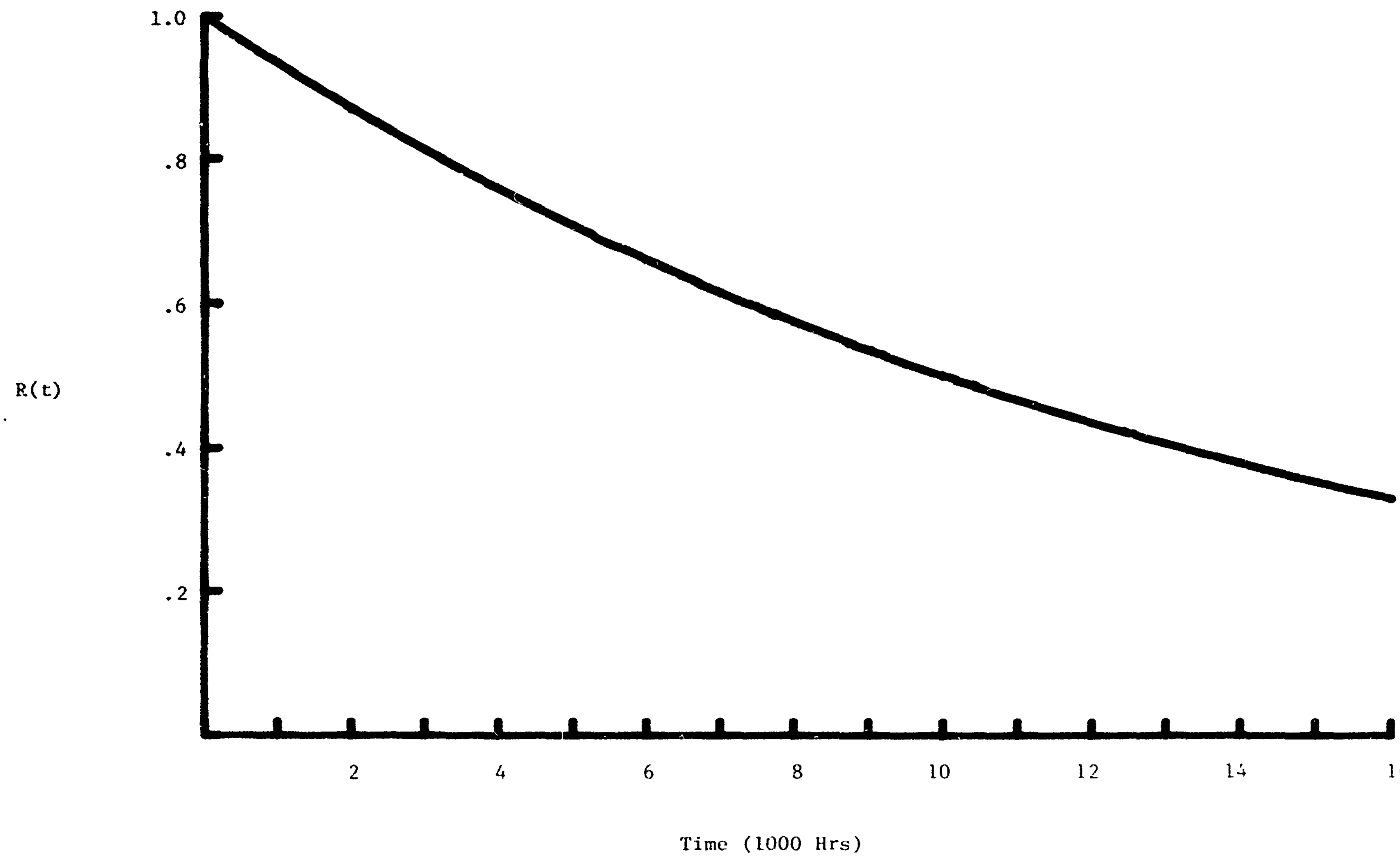


FIGURE A-32 Z5010A KLYSTRON RELIABILITY, R(t)

(λ = 150)

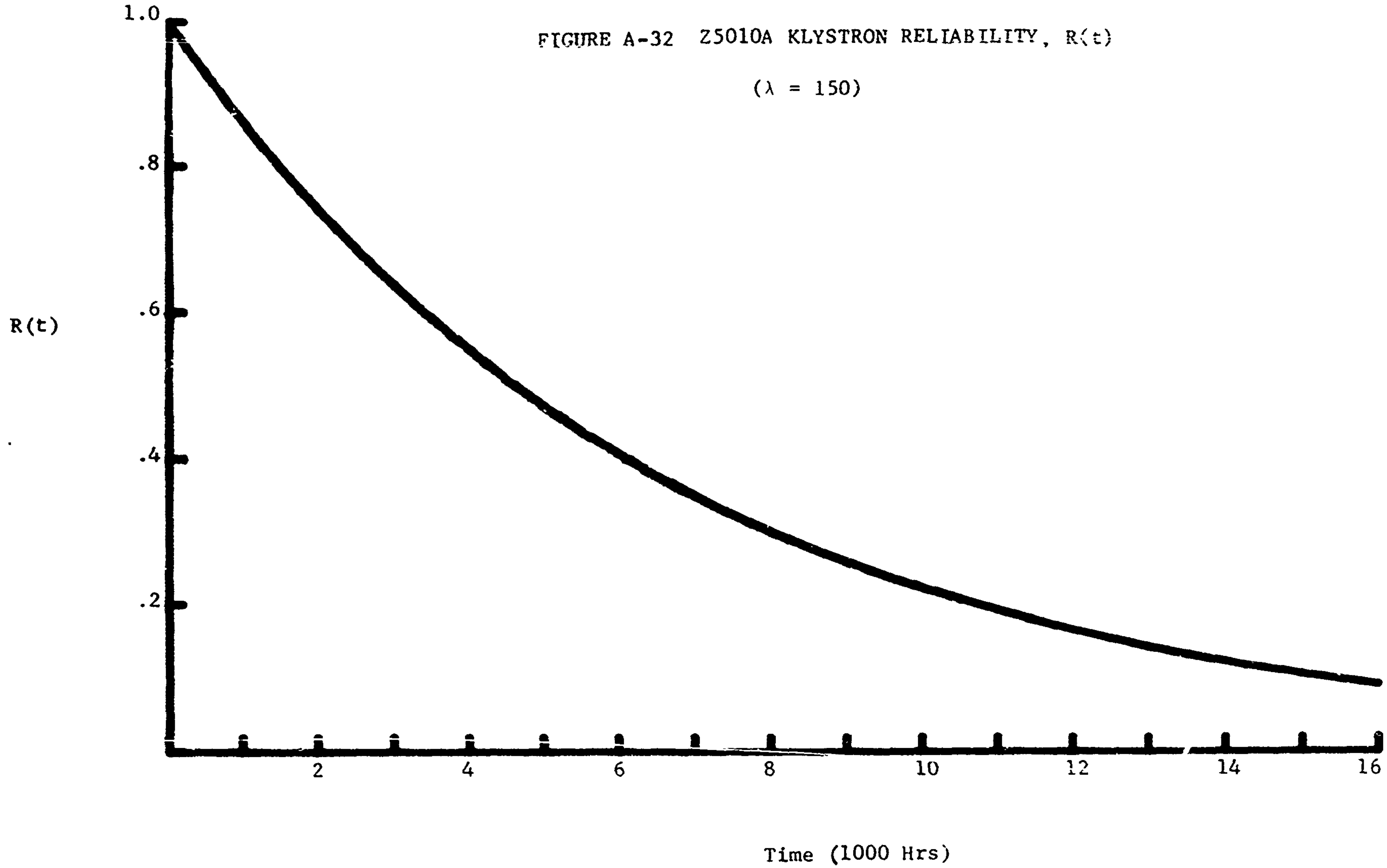


FIGURE A-33 SAC42A KLYSTRON RELIABILITY, R(t)

(λ = 102)

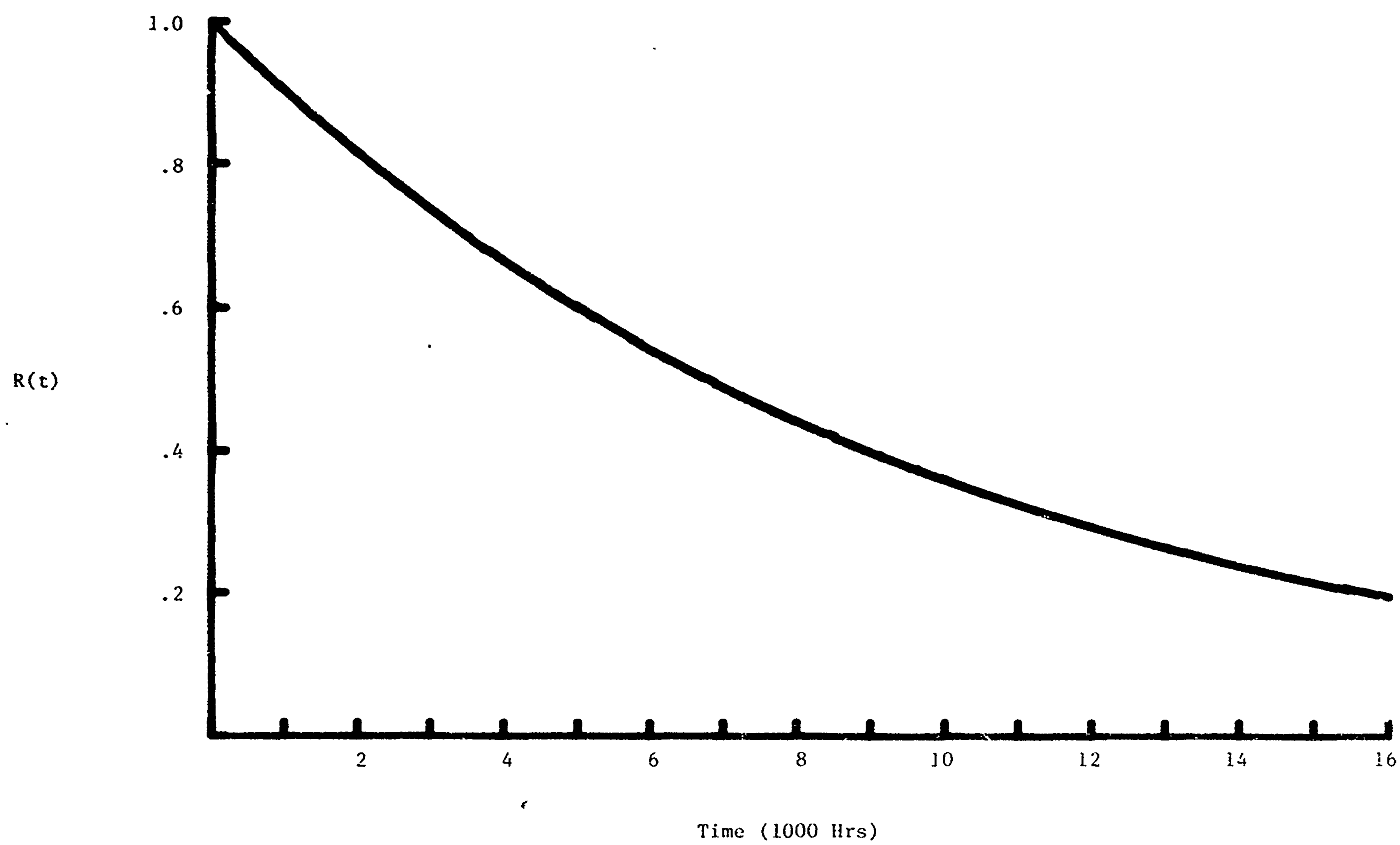


FIGURE A-34 X780D KLYSTRON RELIABILITY, R(t)

(λ = 337)

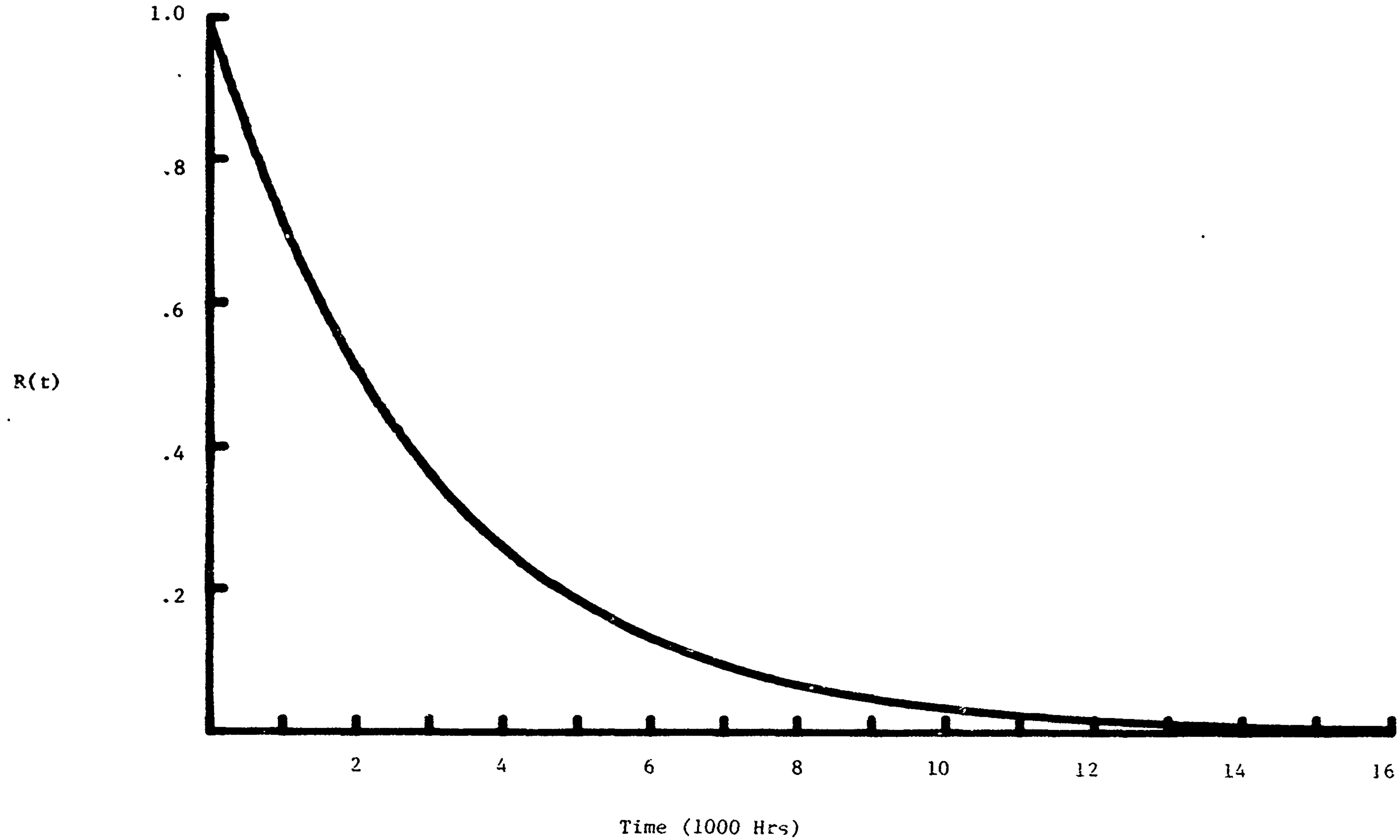


FIGURE A-35 L3035 KLYSTRON RELIABILITY, R(t)

(λ = 66)

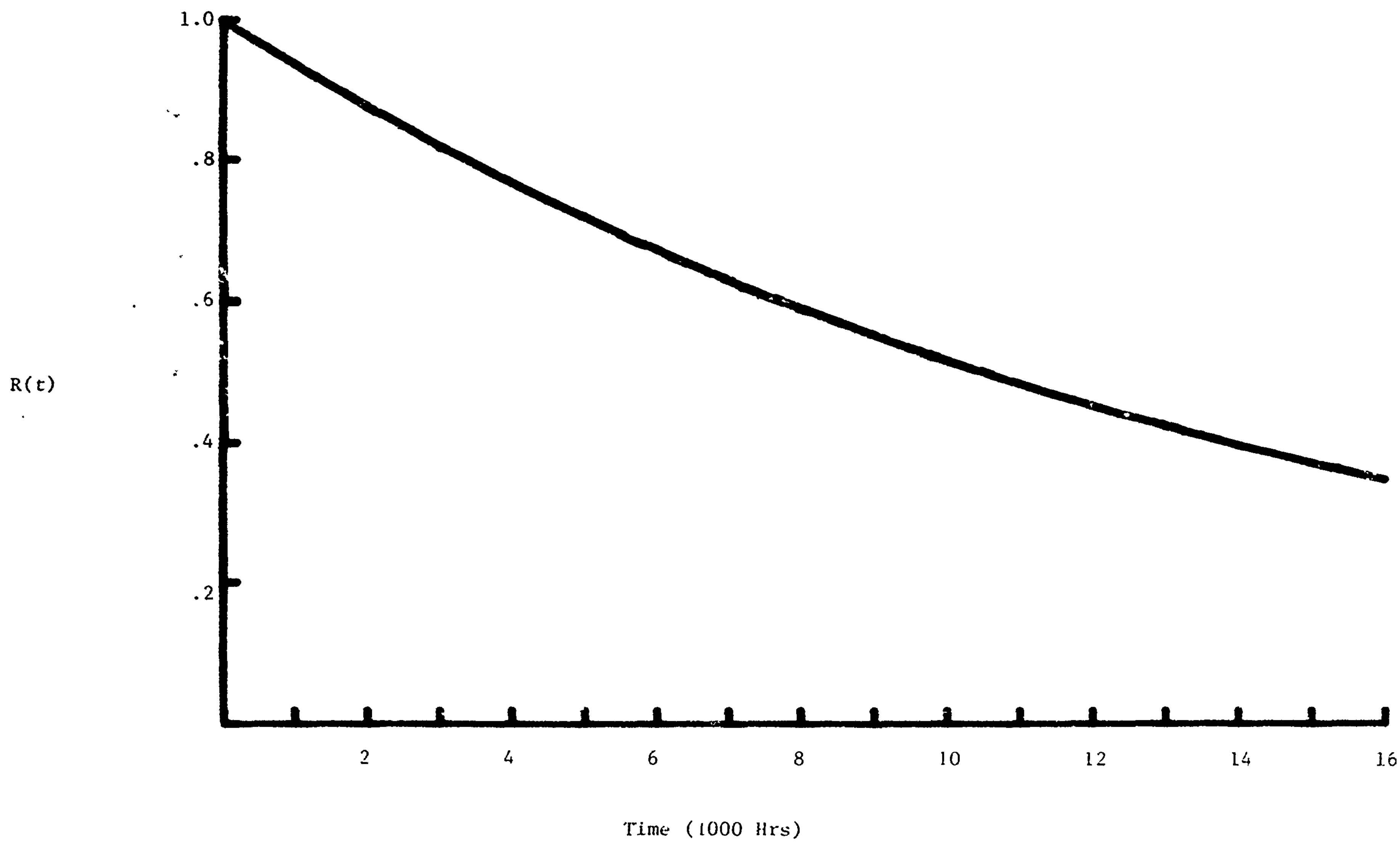


FIGURE A-36 VA842 KLYSTRON RELIABILITY, R(t)

(λ = 18)

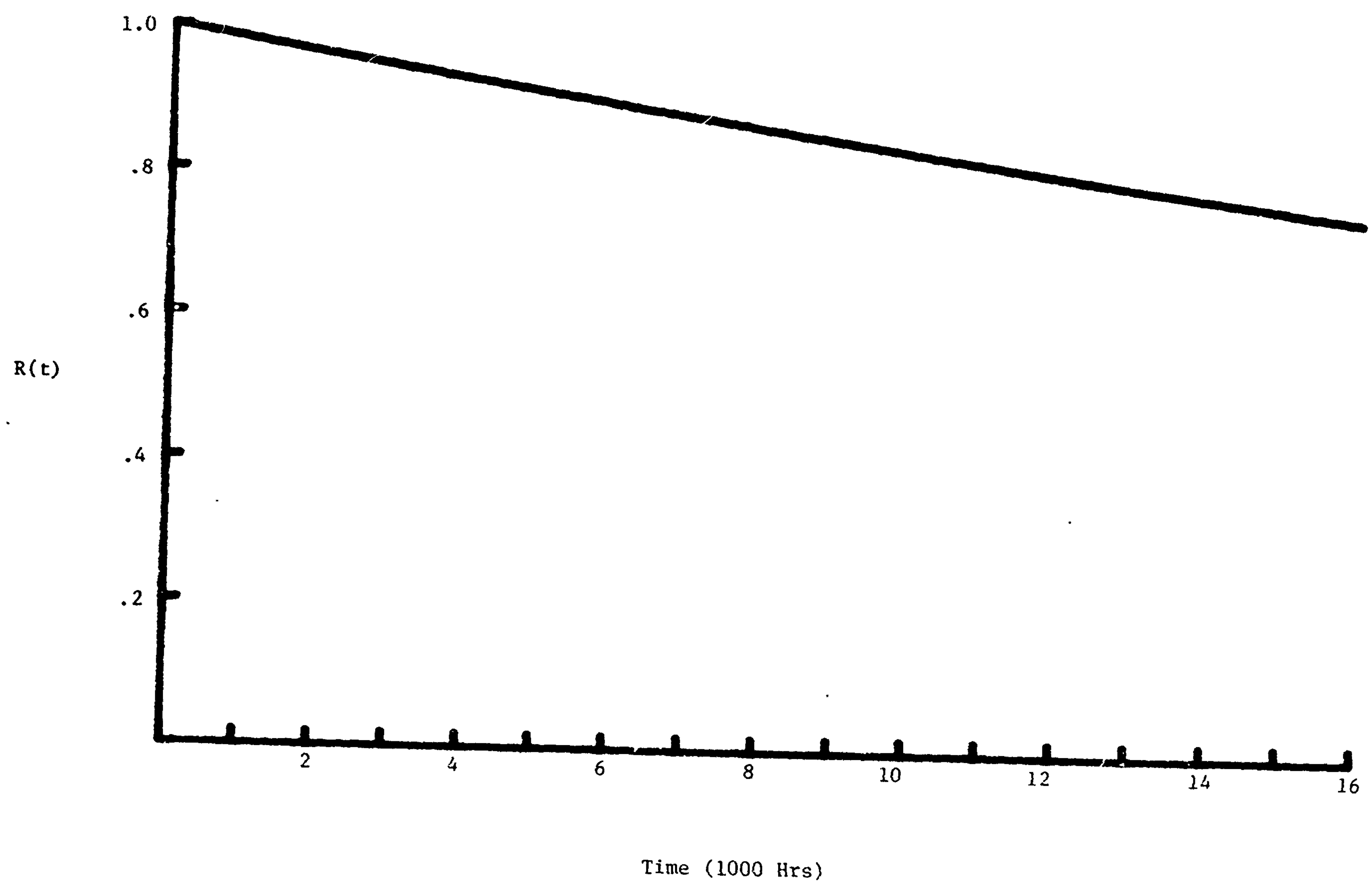


FIGURE A-37 L3403 KLYSTRON RELIABILITY, R(t)

($\lambda = 93$)

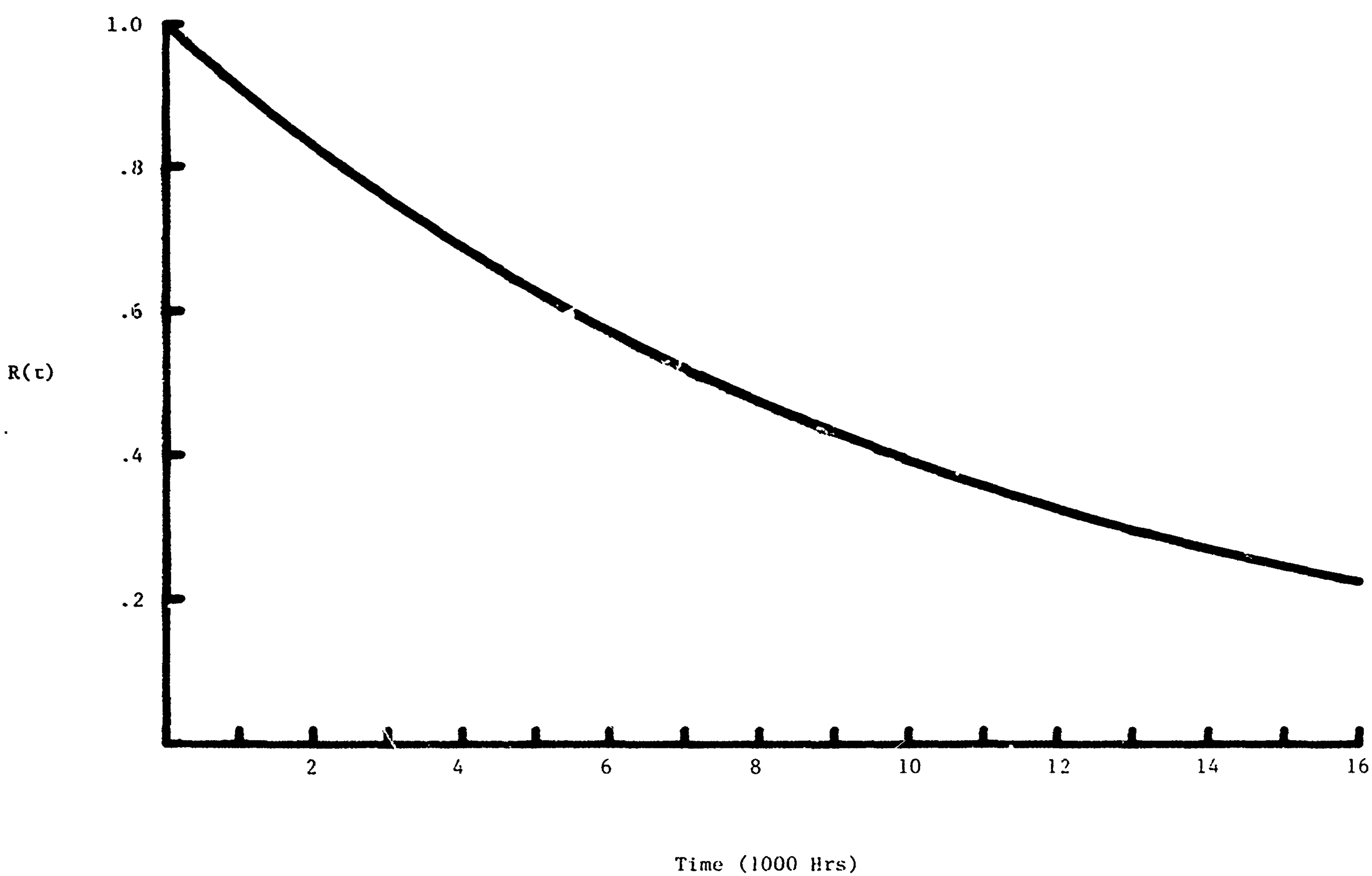


FIGURE A-38 4KMP10000LF KLYSTRON RELIABILITY, R(t)

(λ = 43)

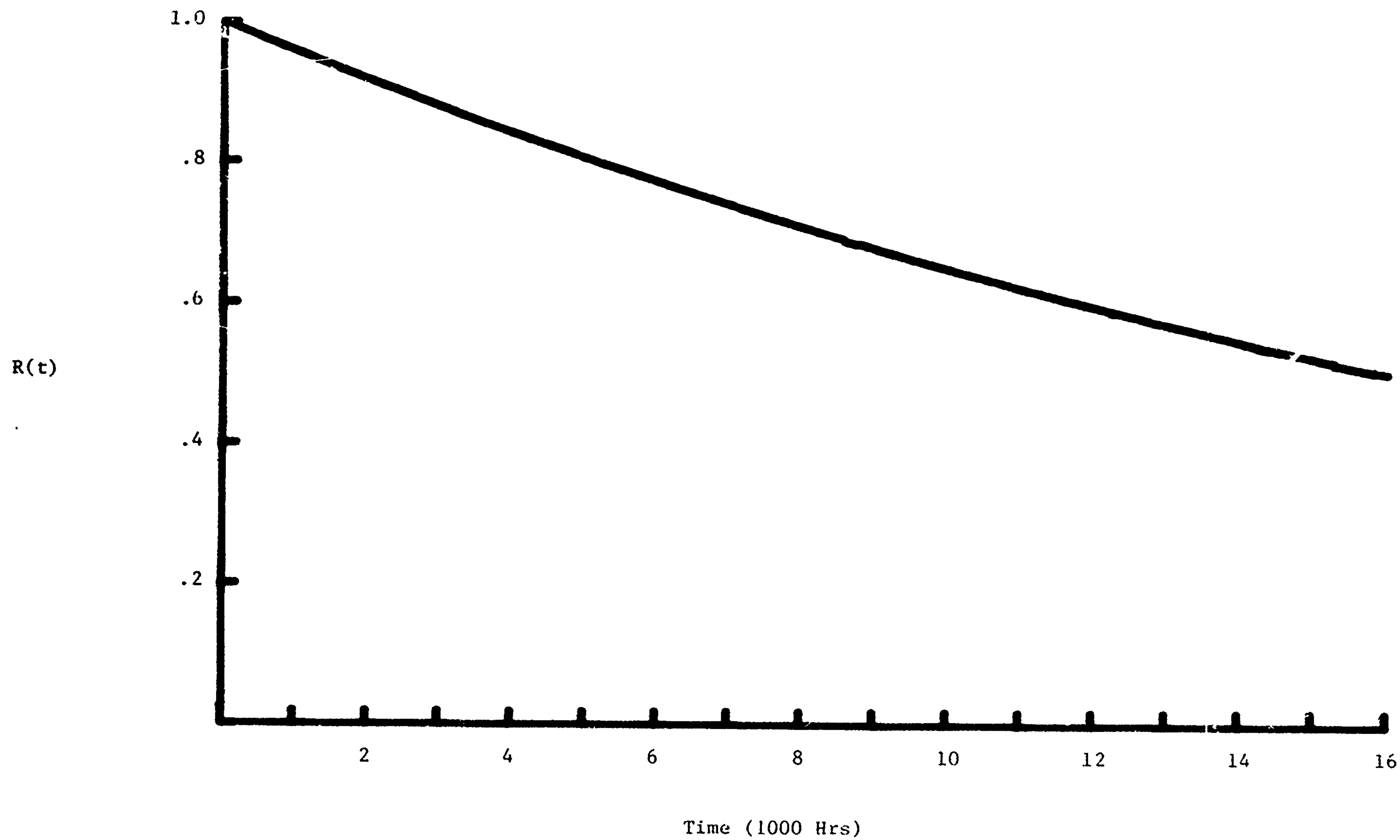


FIGURE A-39 VTR5210A1 TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 145)

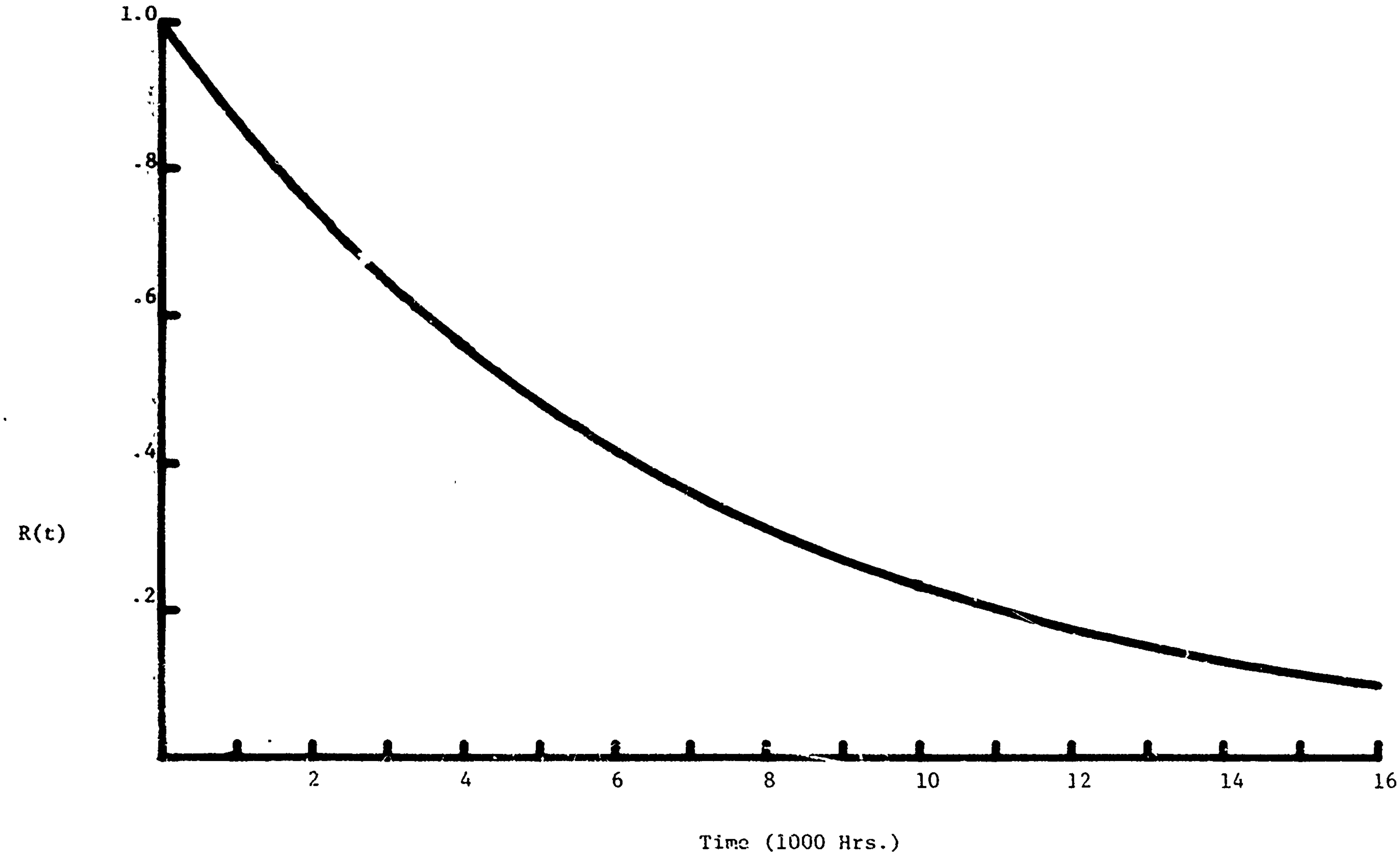


FIGURE A-40 ZM3167 TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 88)

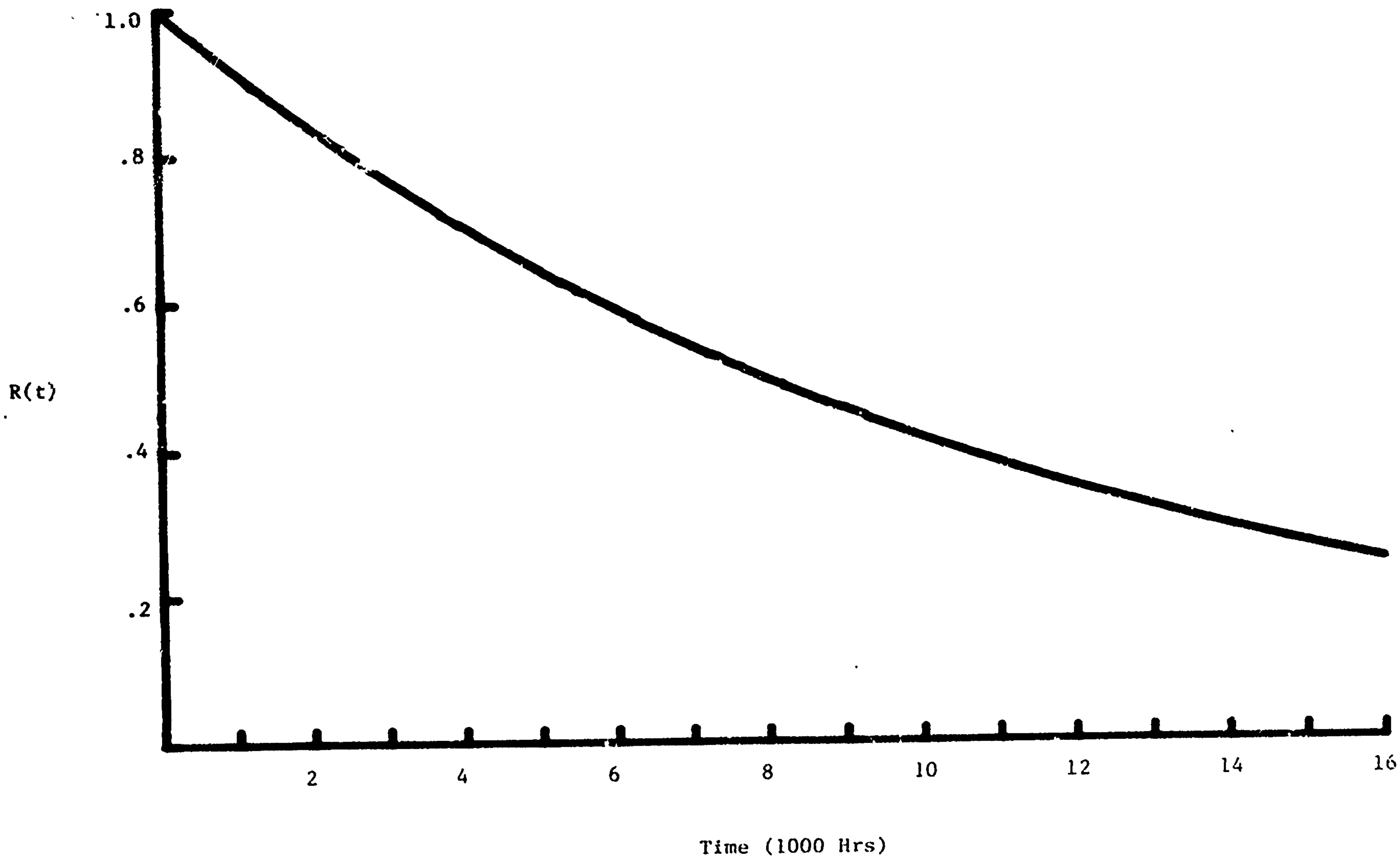


FIGURE A-41 MA2001A TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 165)

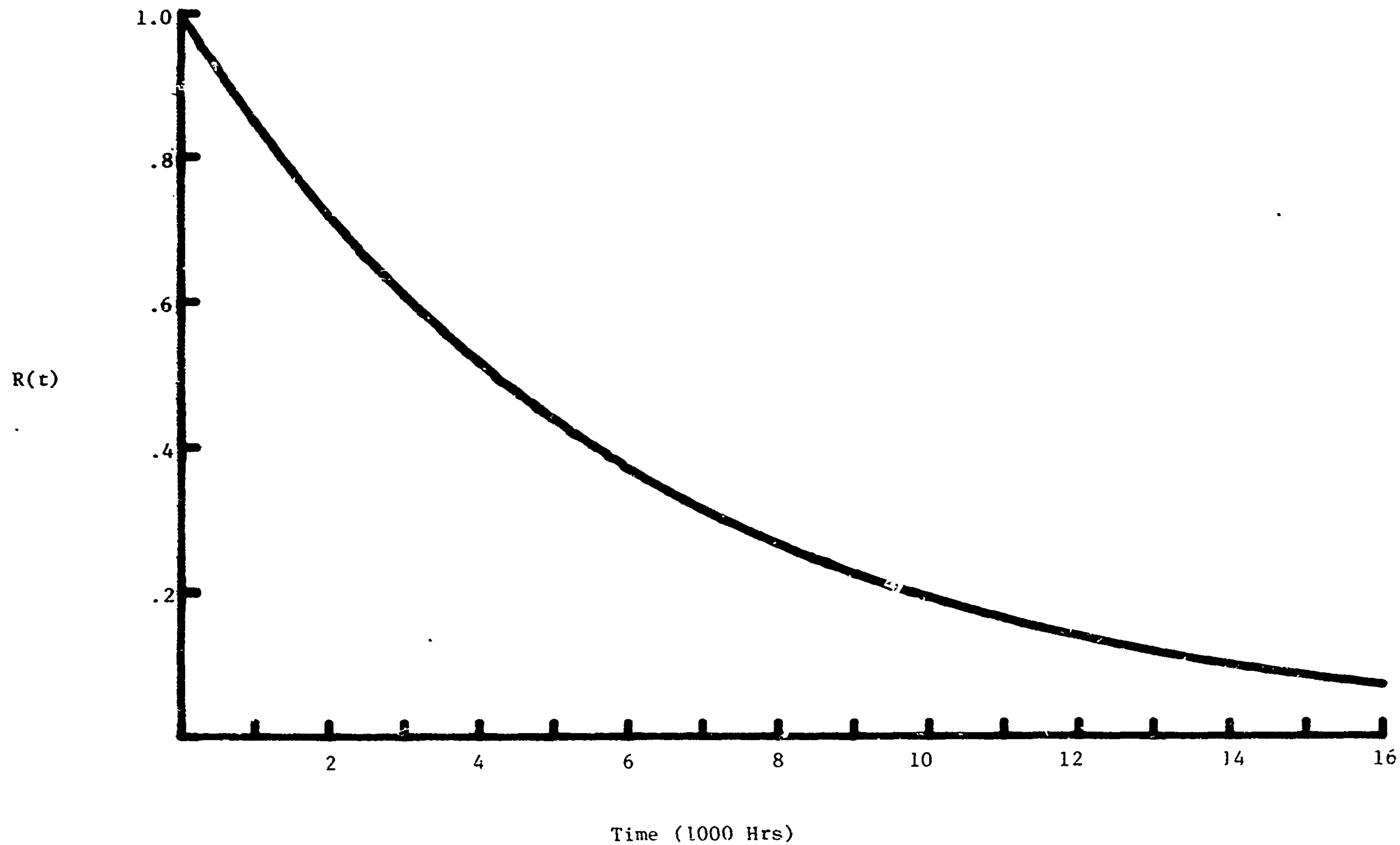


FIGURE A-42 VA138D TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 53)

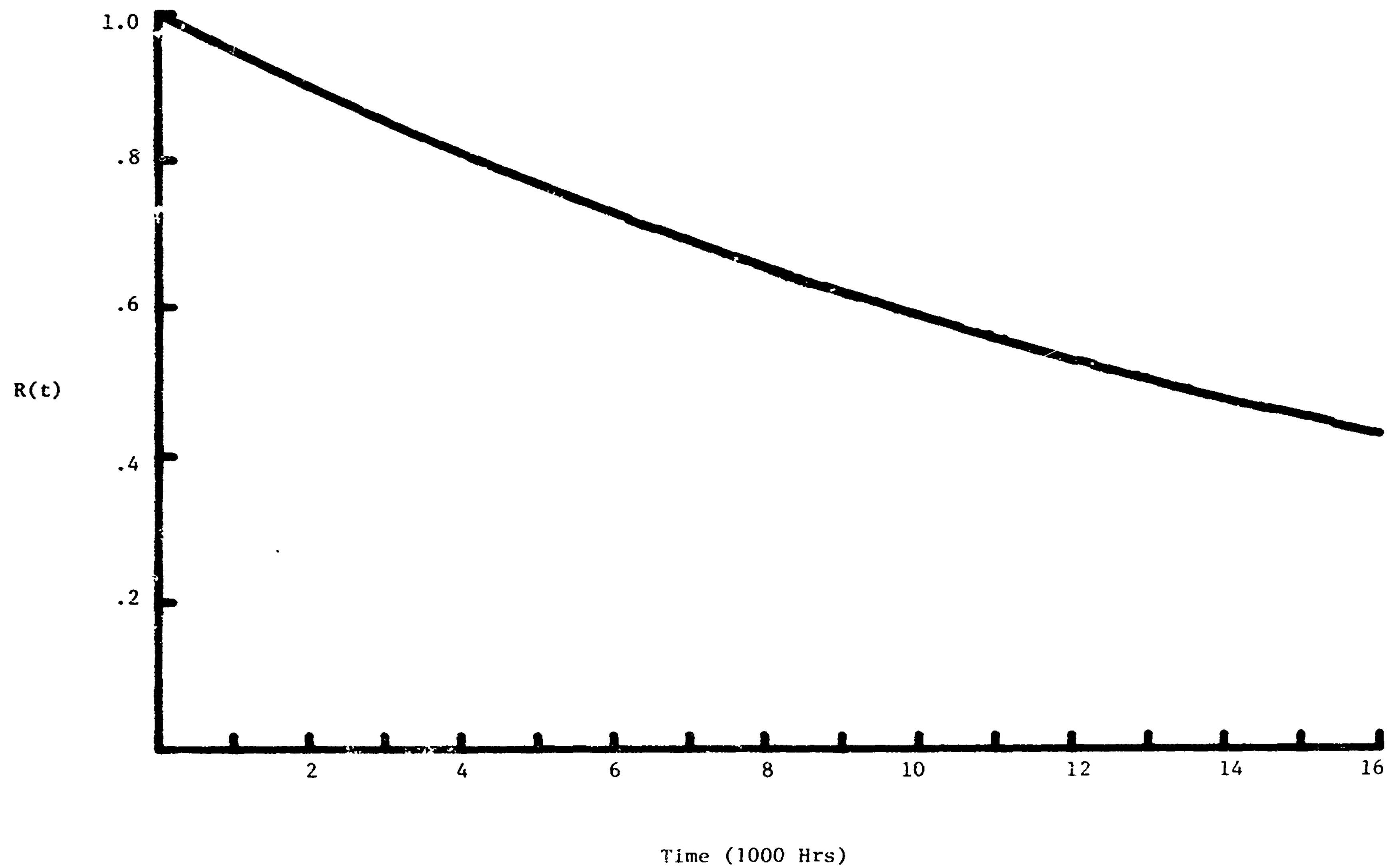


FIGURE A-43 WJ3751 TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 90)

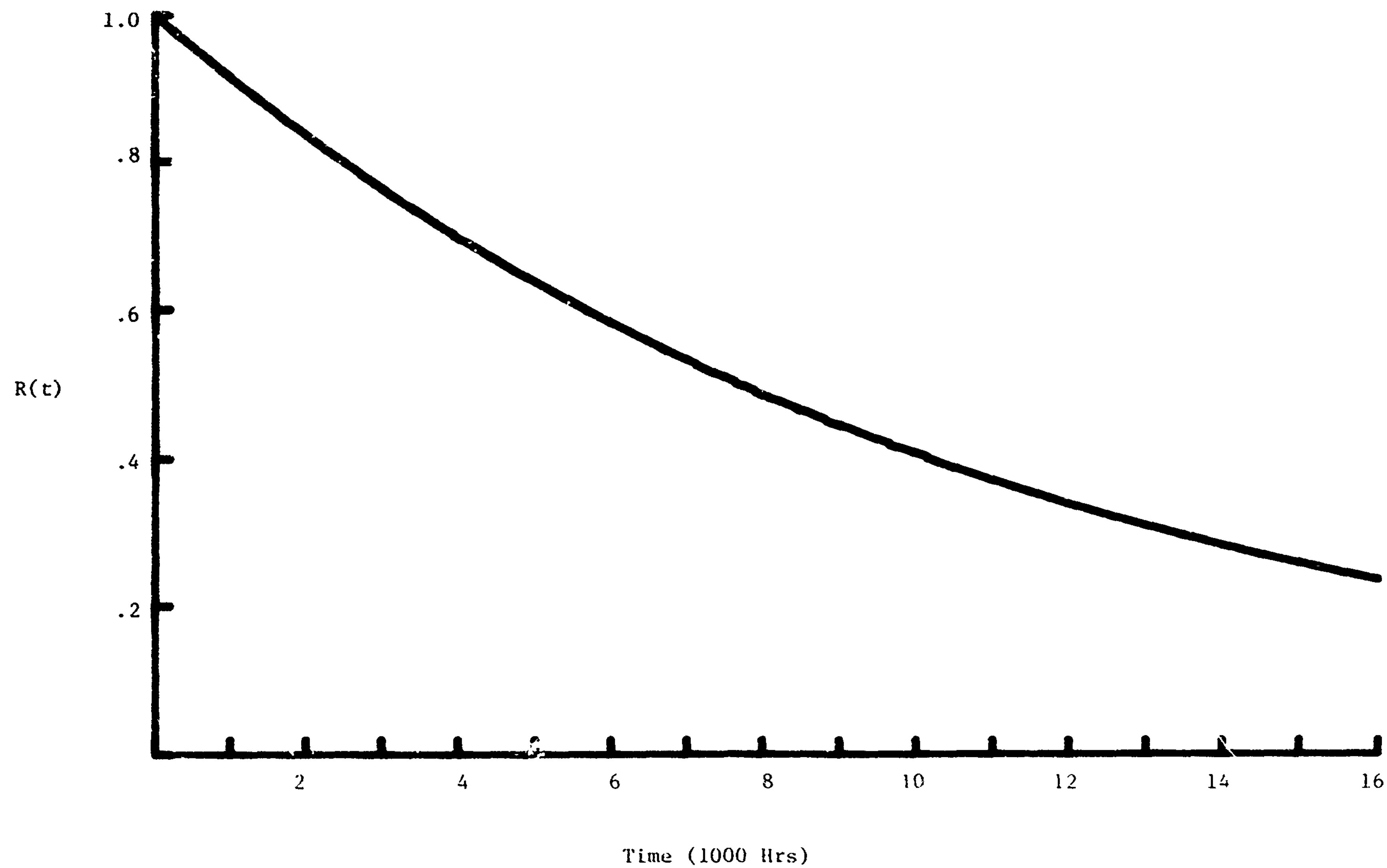


FIGURE A-44 M5768 TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 2203)

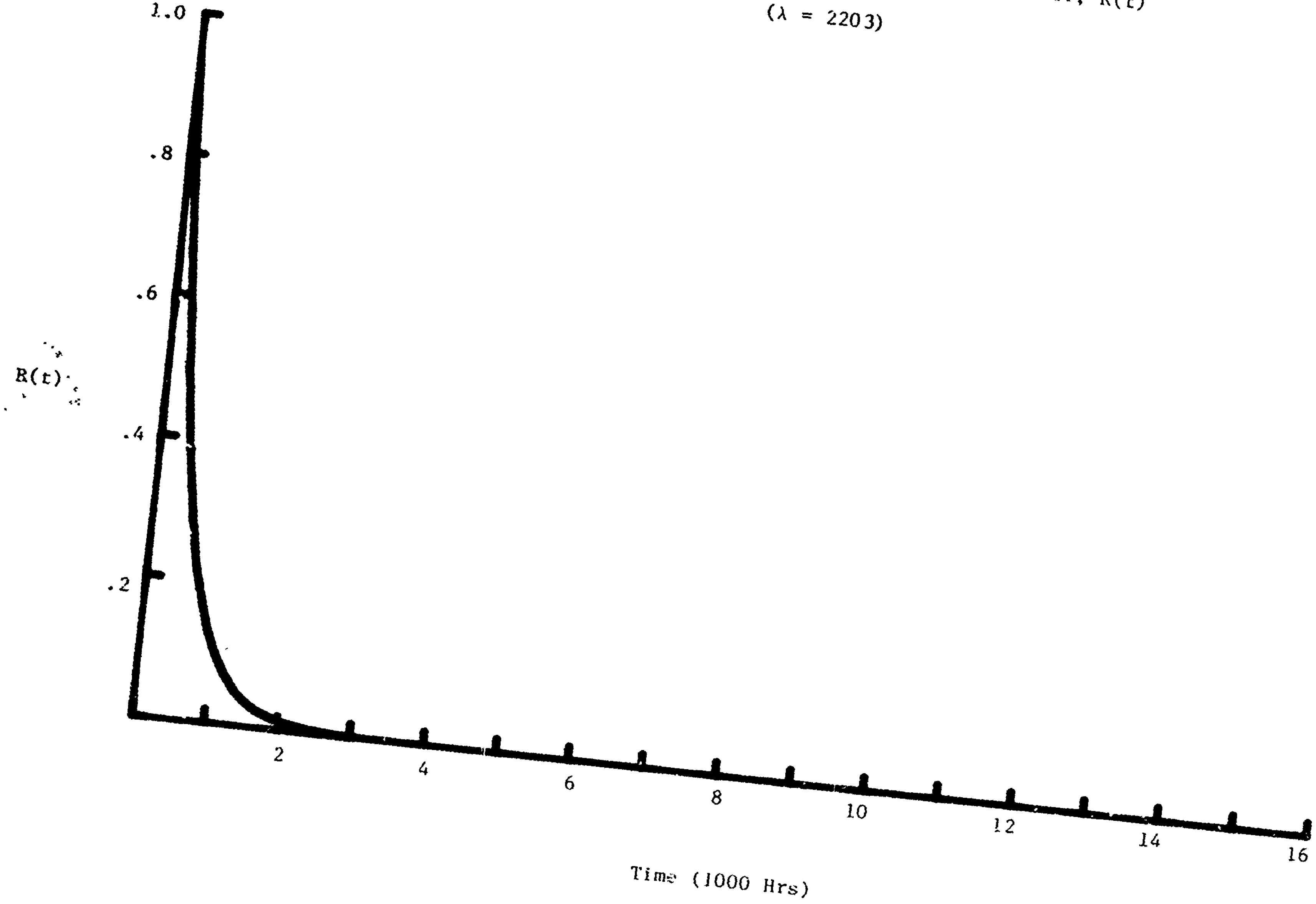


FIGURE A-45 VA643 TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 607)

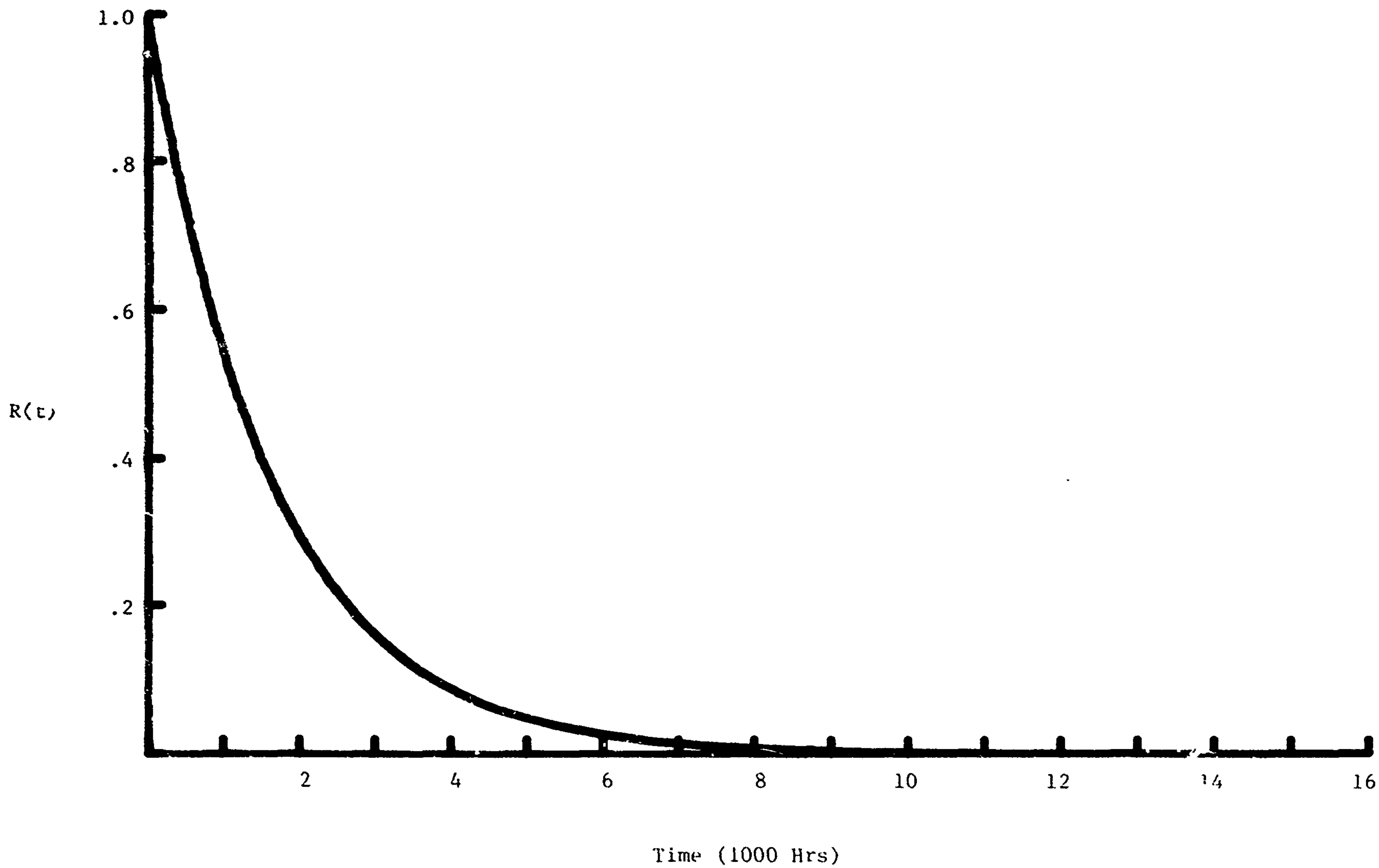


FIGURE A-46 ALQ94HB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 4530)

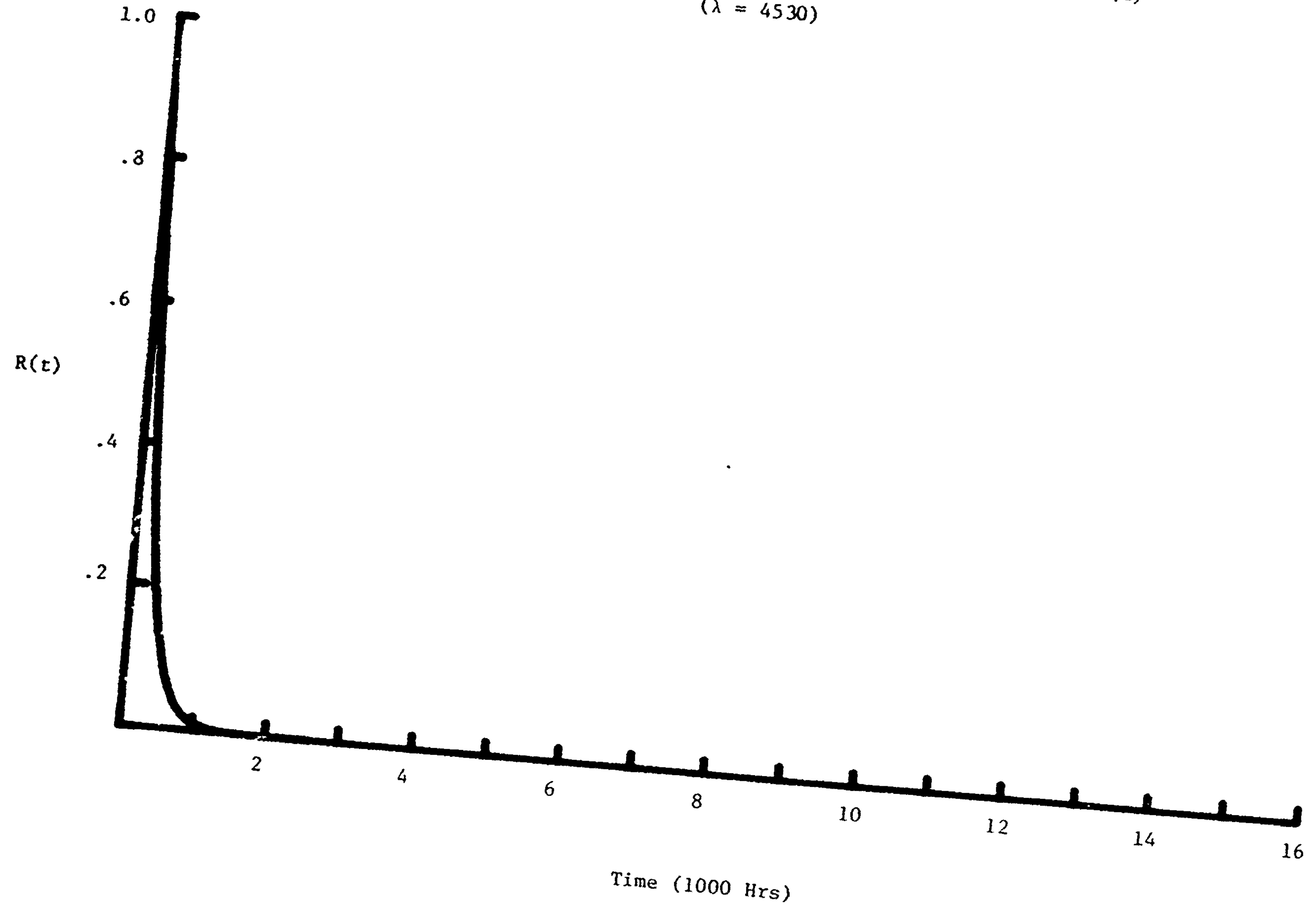


FIGURE A-47 ALQ94MB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 4470)

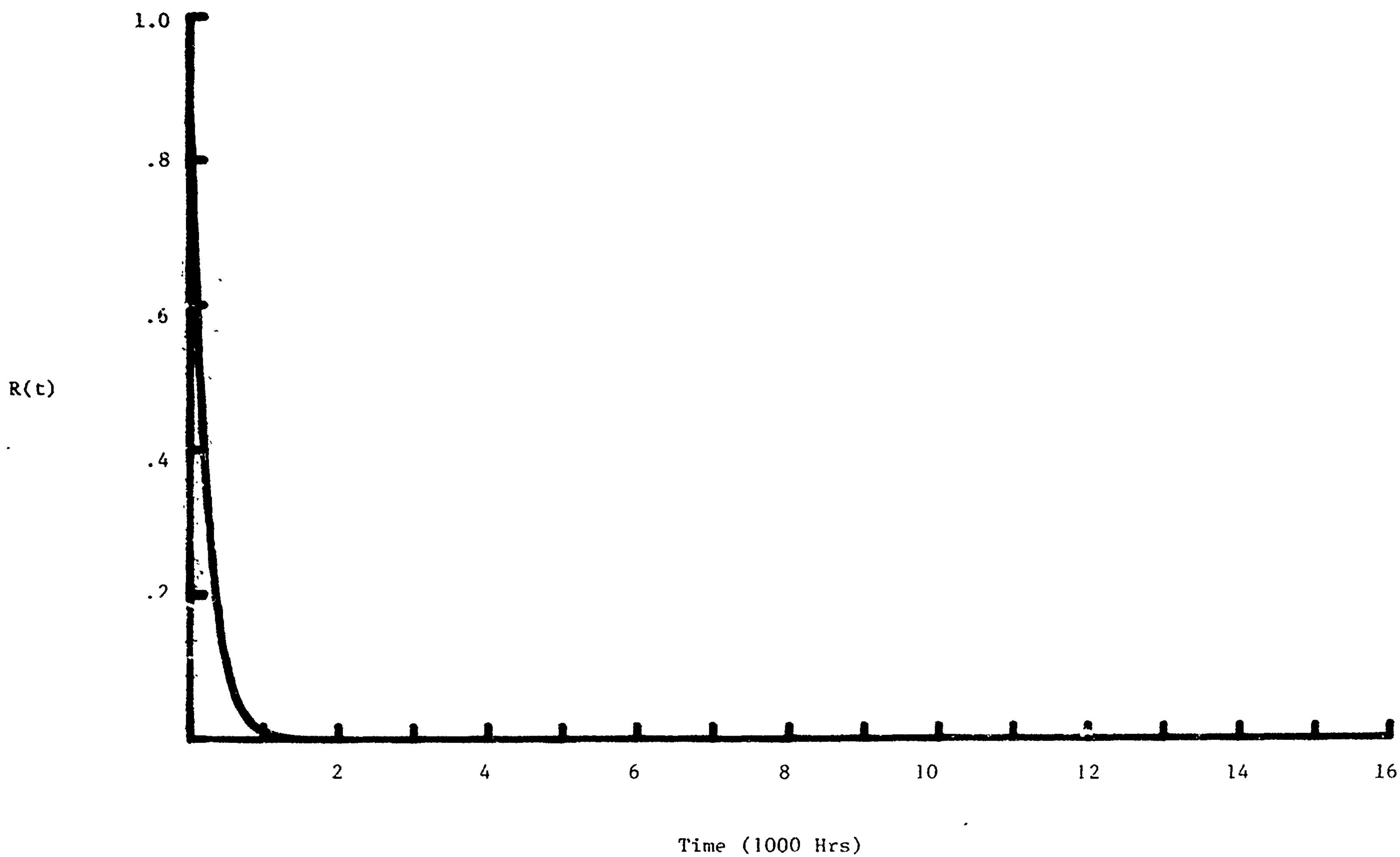


FIGURE A-48 ALQ94LB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 1865)

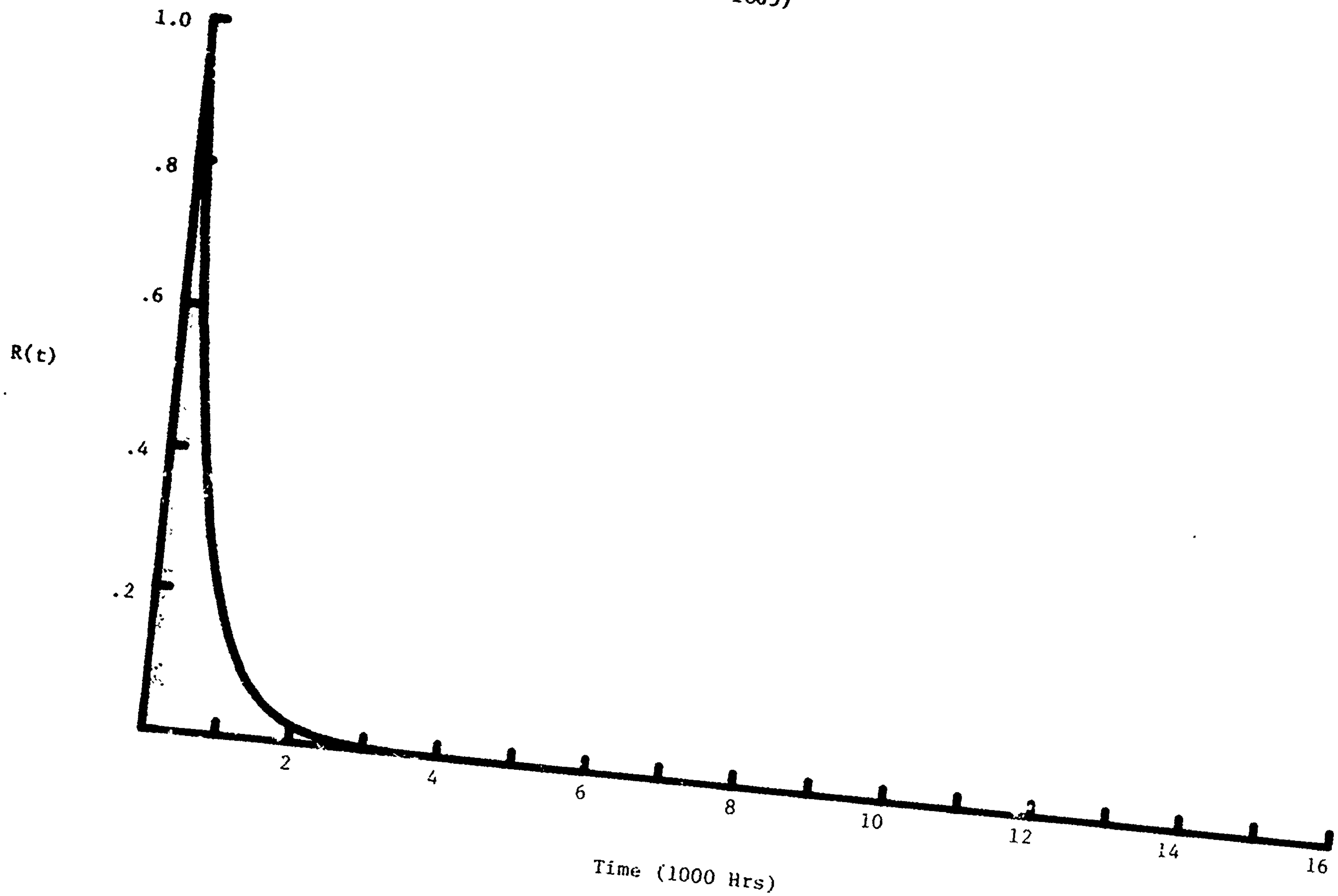


FIGURE A-49 ALQ101MB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 4350)

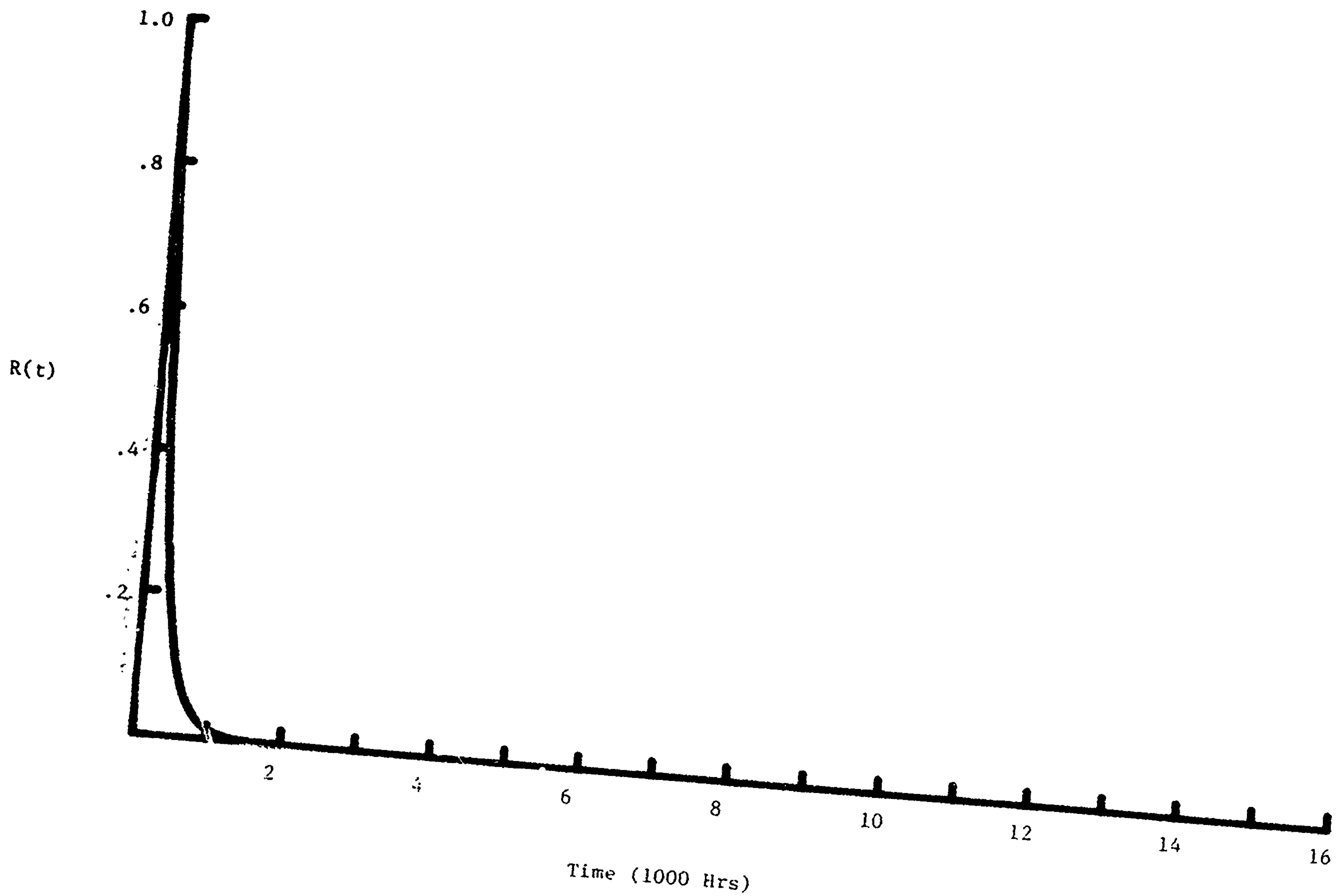


FIGURE A-50 ALQ101LB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 4350)

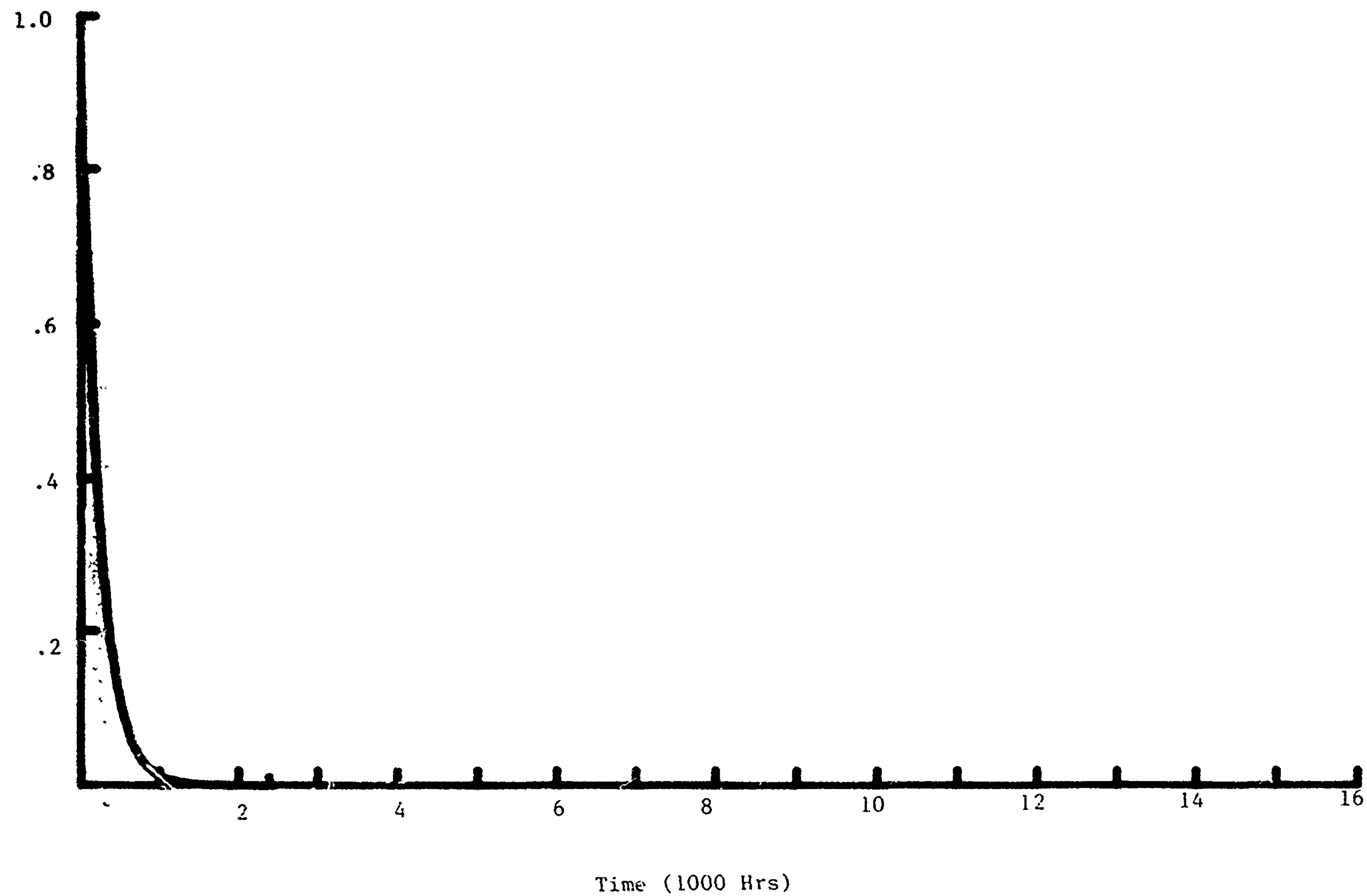


FIGURE A-51 ALQ177 TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 1100)

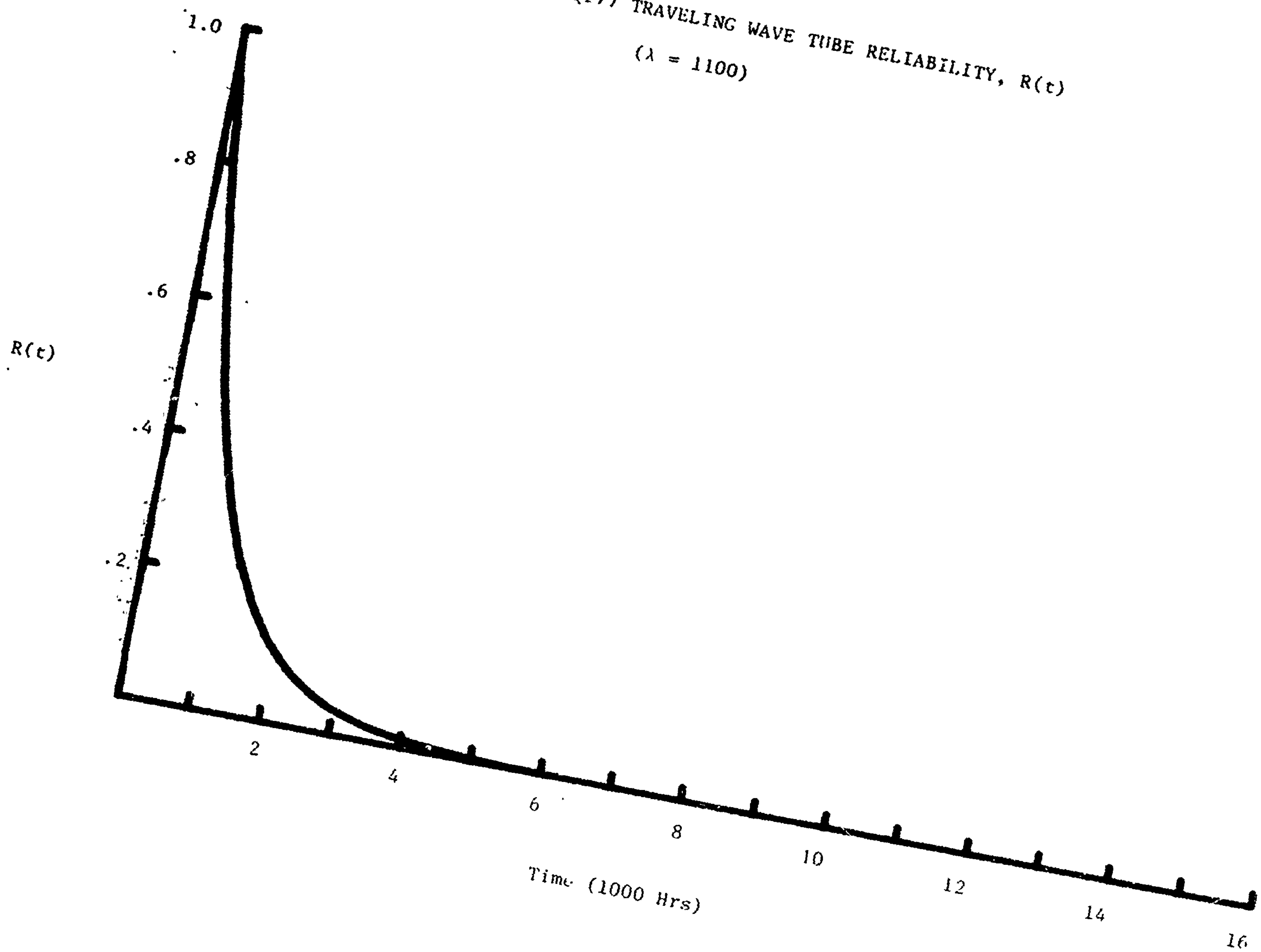


FIGURE A-52 ALQ117HB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 910)

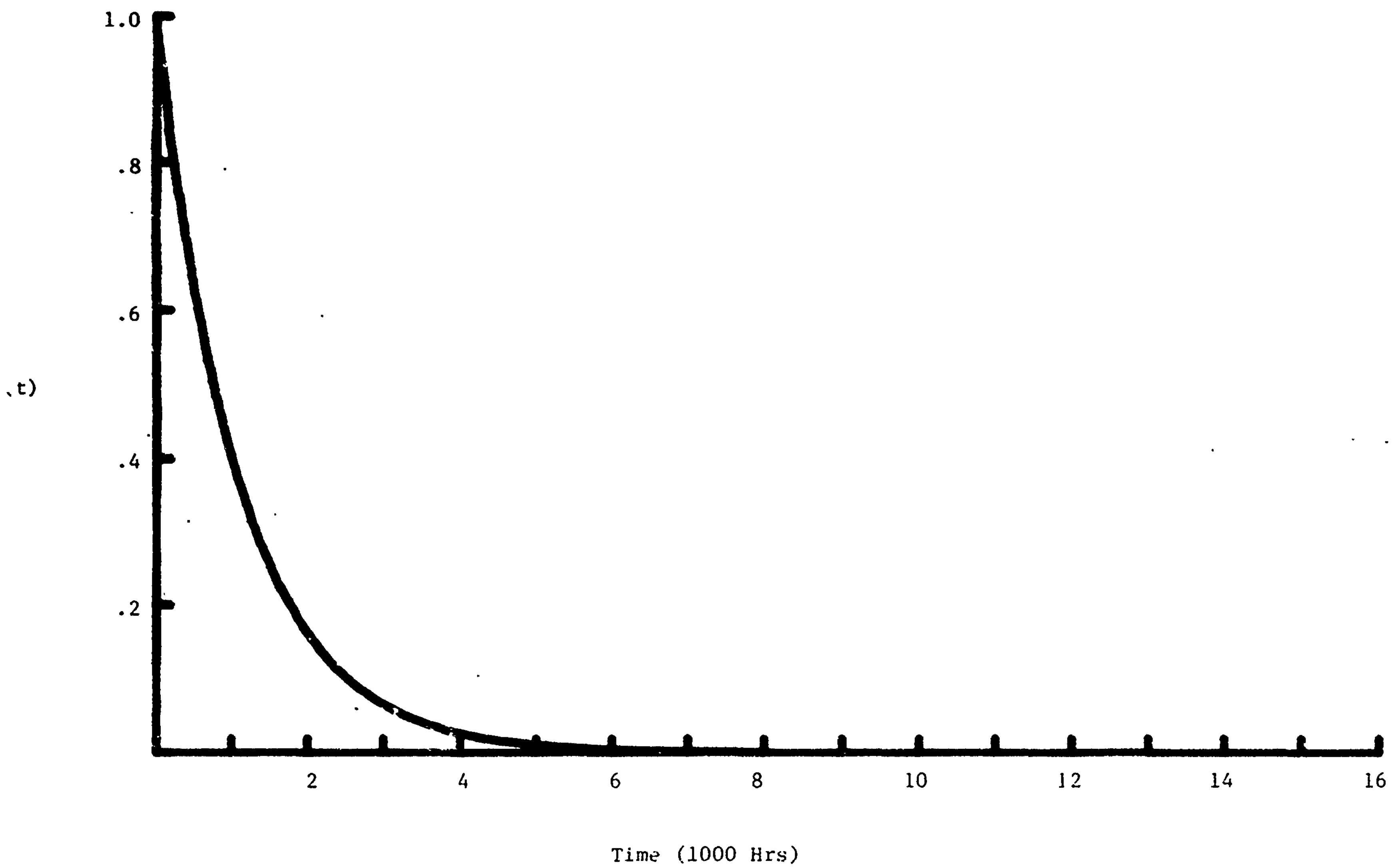


FIGURE A-53 ALQ119HB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 1475)

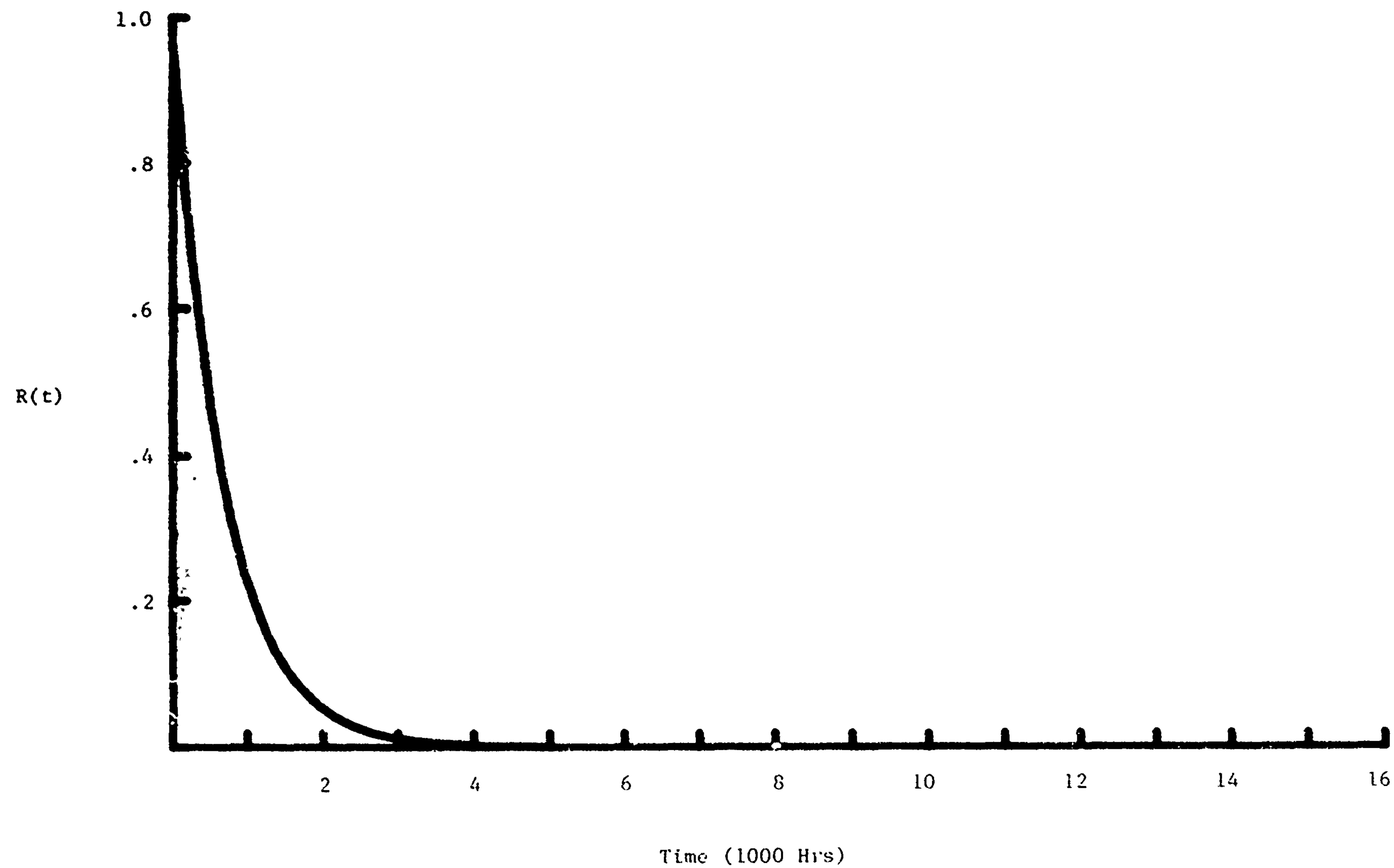


FIGURE A-54 ALQ119MB TRAVELING WAVE TUBE RELIABILITY, R(t)

(λ = 1185)

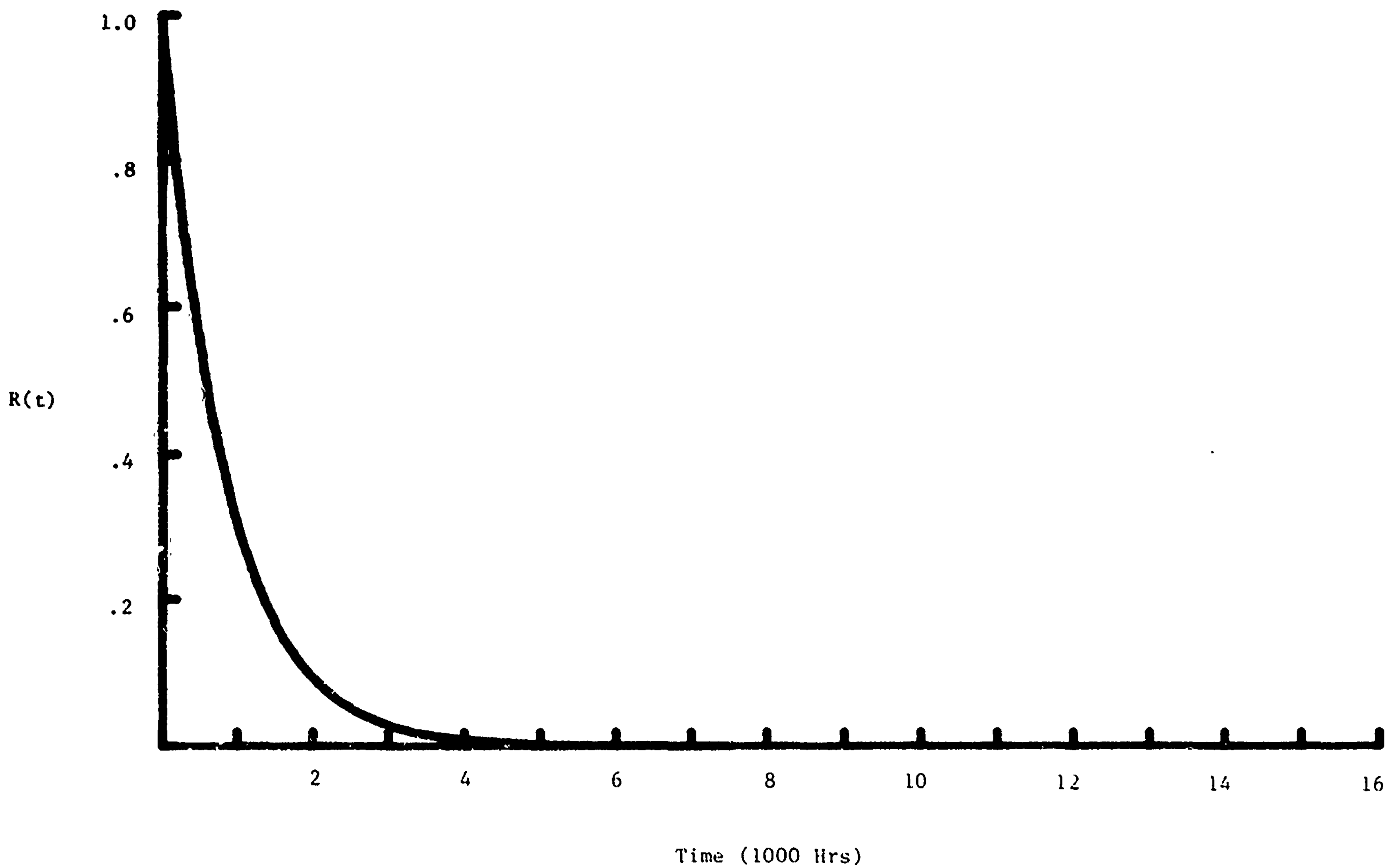


FIGURE A-55 ALQ119LB TRAVELING WAVE TUBE REALIBILITY, R(t)

(λ = 1460)

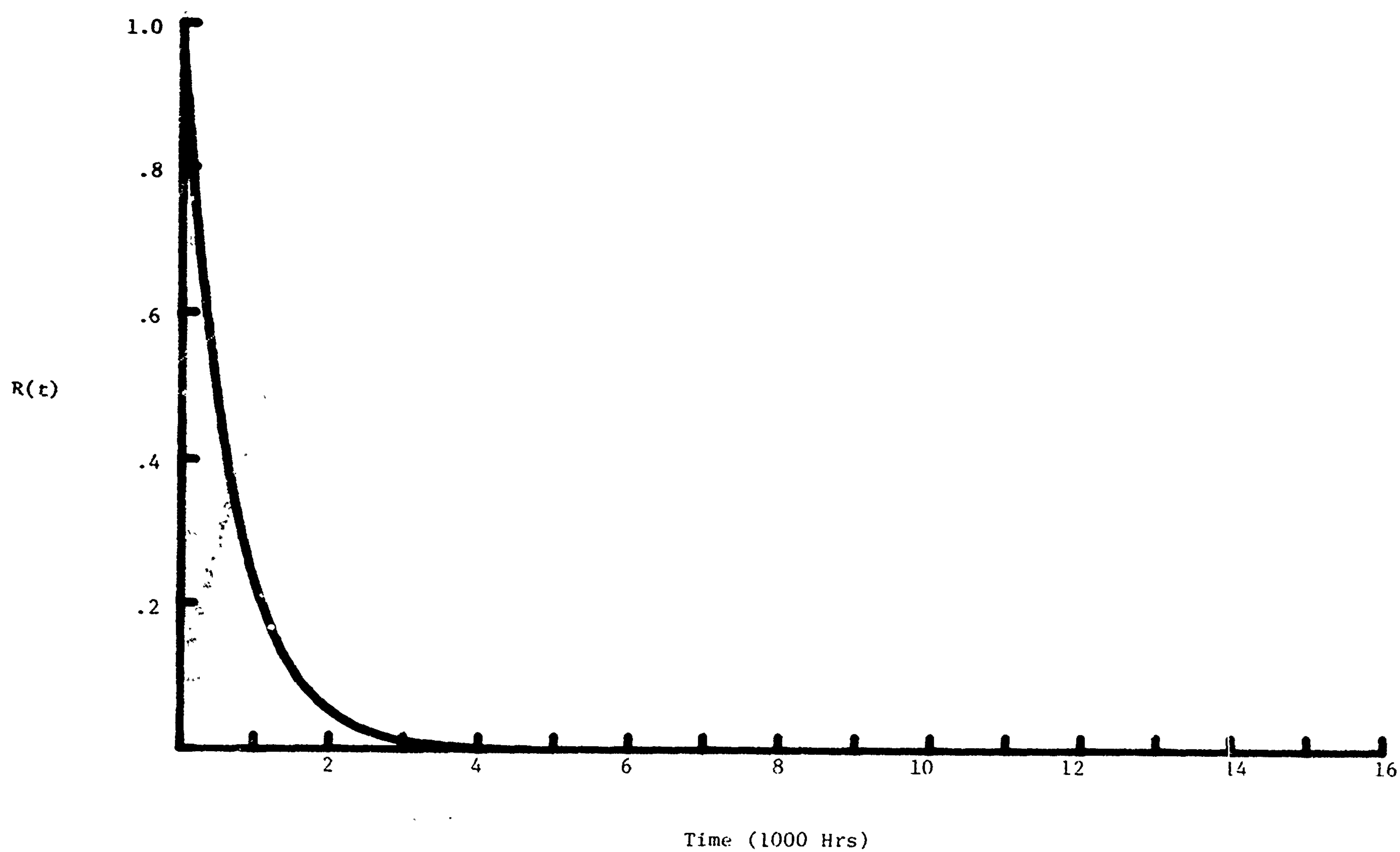


FIGURE A-56 QK338A MAGNETRON RELIABILITY, R(t)

(λ = 463)

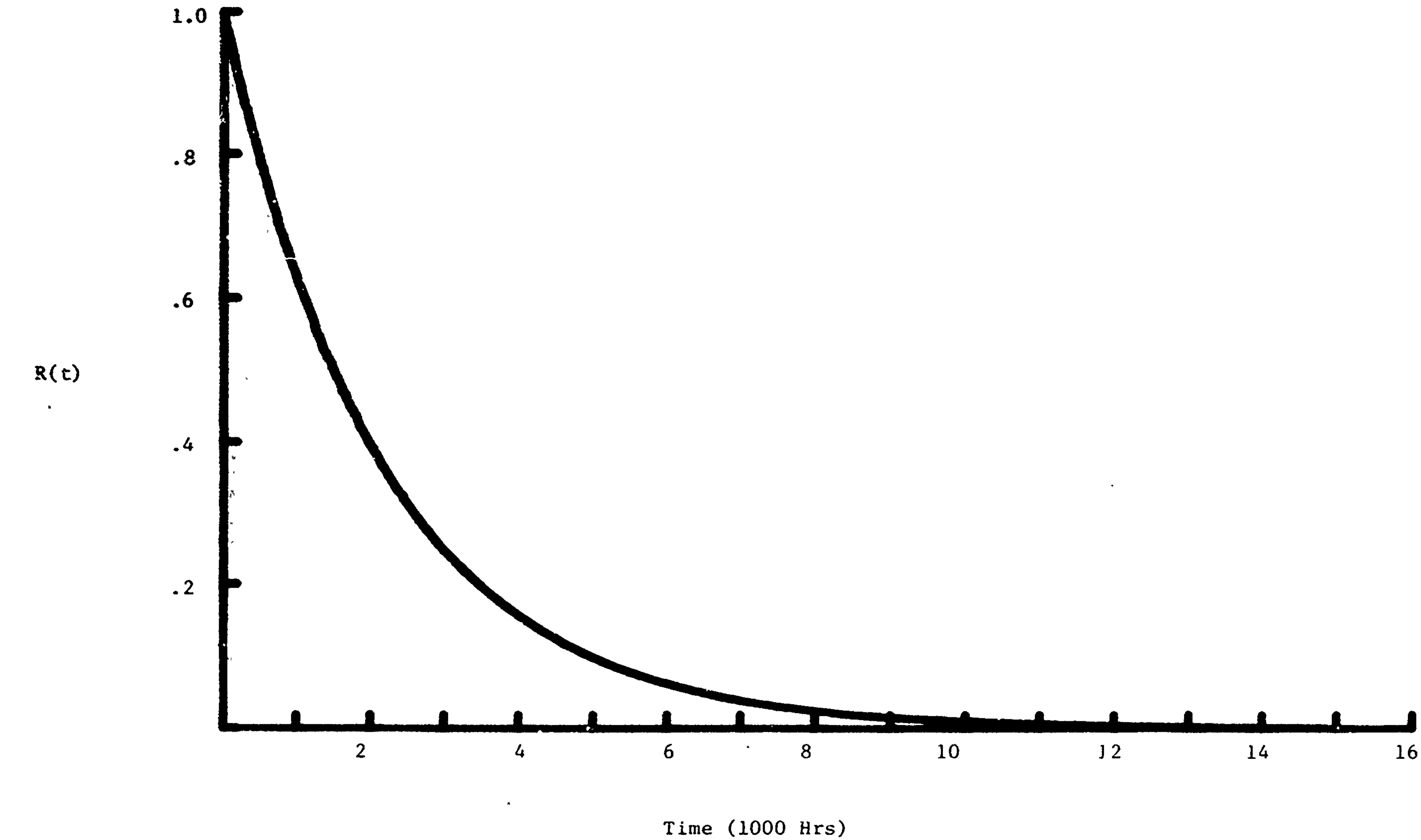


FIGURE A-57 6410A (MANUFACTURER'S DATA) MAGNETRON RELIABILITY, R(t)

(λ = 535)

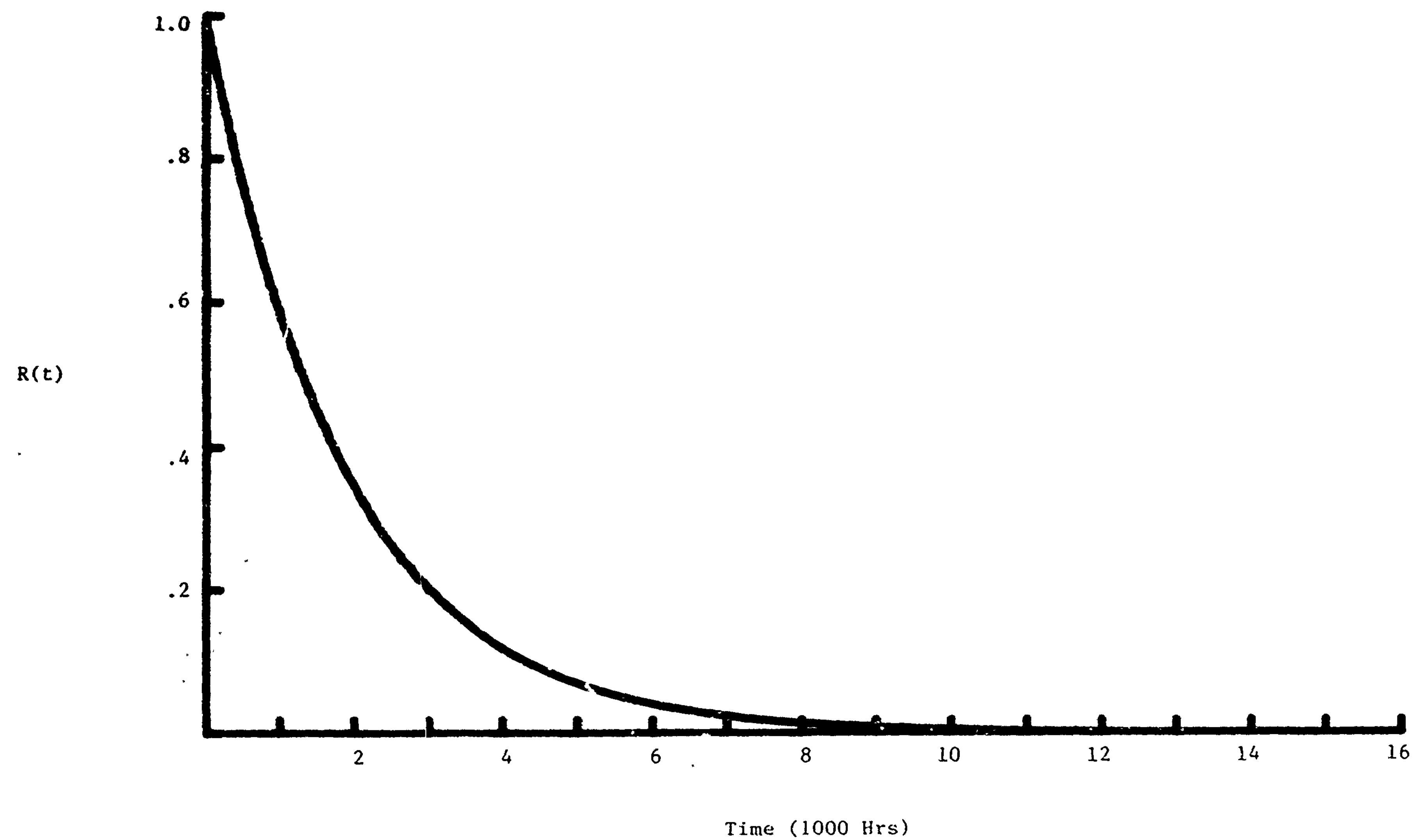


FIGURE A-58 7529 (MANUFACTURER'S DATA) MAGNETRON RELIABILITY
(λ = 353)

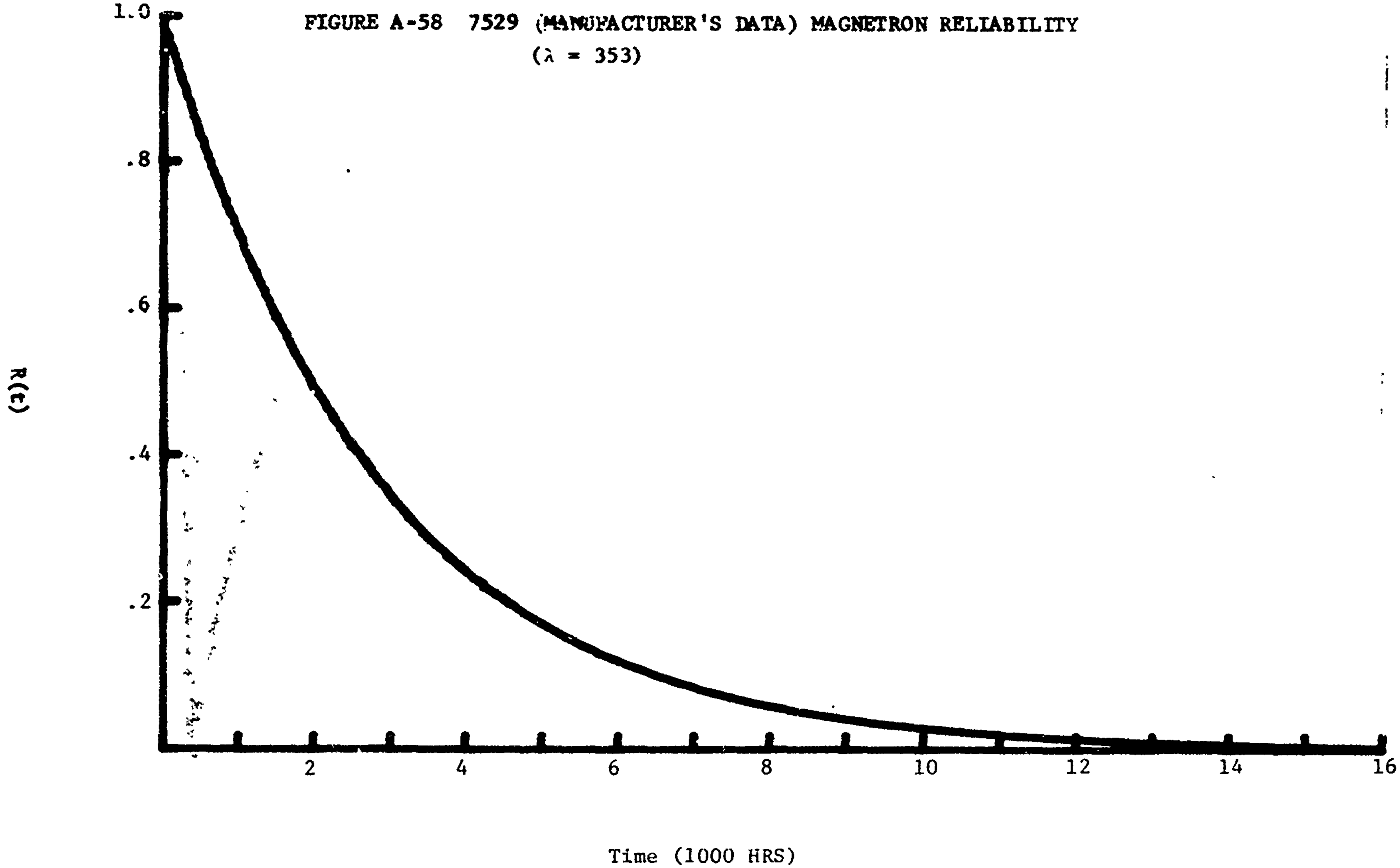


FIGURE A-59 QK327A MAGNETRON RELIABILITY, R(t)

(λ = 432)

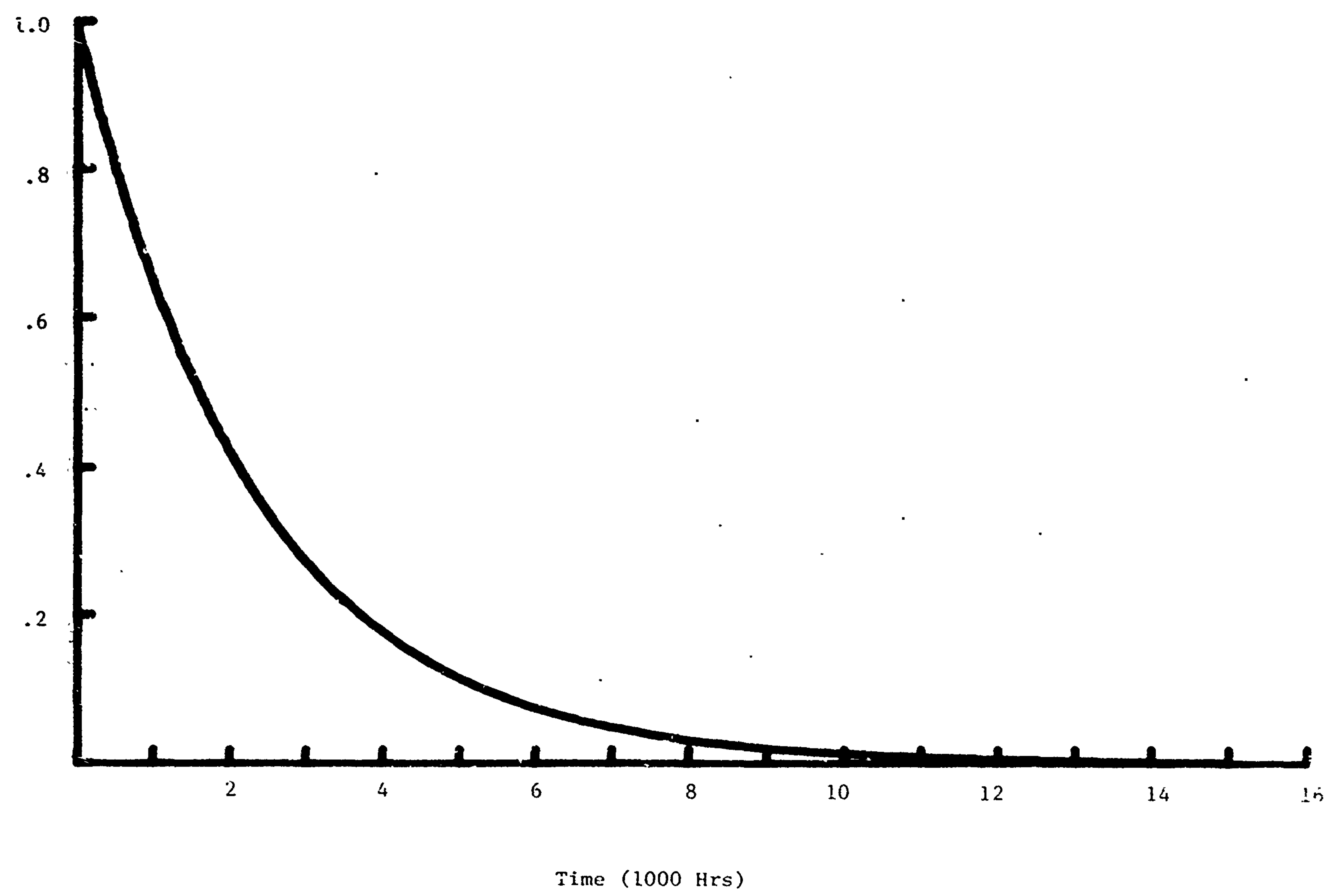


FIGURE A-60 QK327A (MANUFACTURER'S DATA) MAGNETRON RELIABILITY, R(t)

(λ = 367)

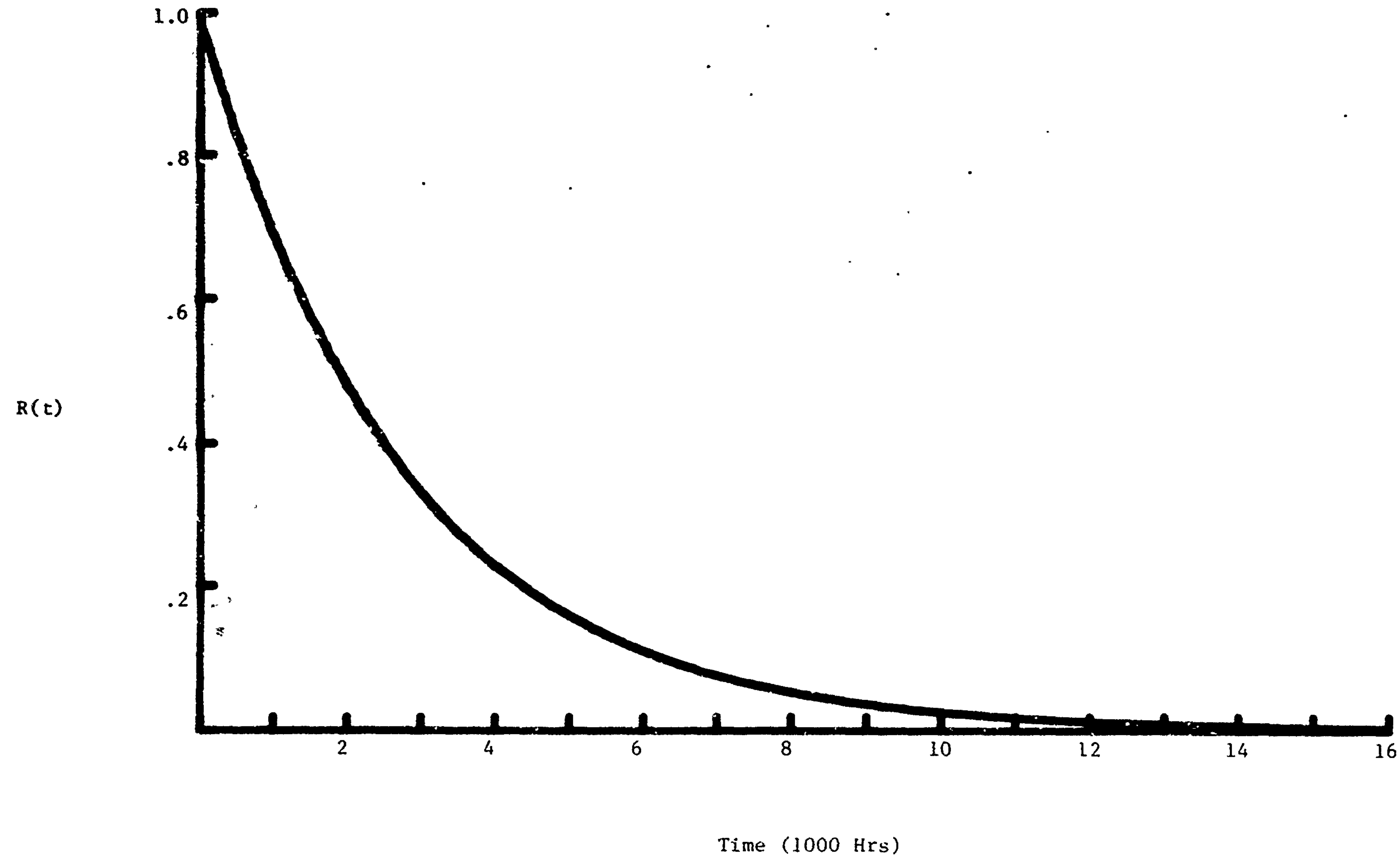


FIGURE A-61 SFD356 (MANUFACTURER'S DATA) COAXIAL MAGNETRON RELIABILITY, R(t)

(λ = 125)

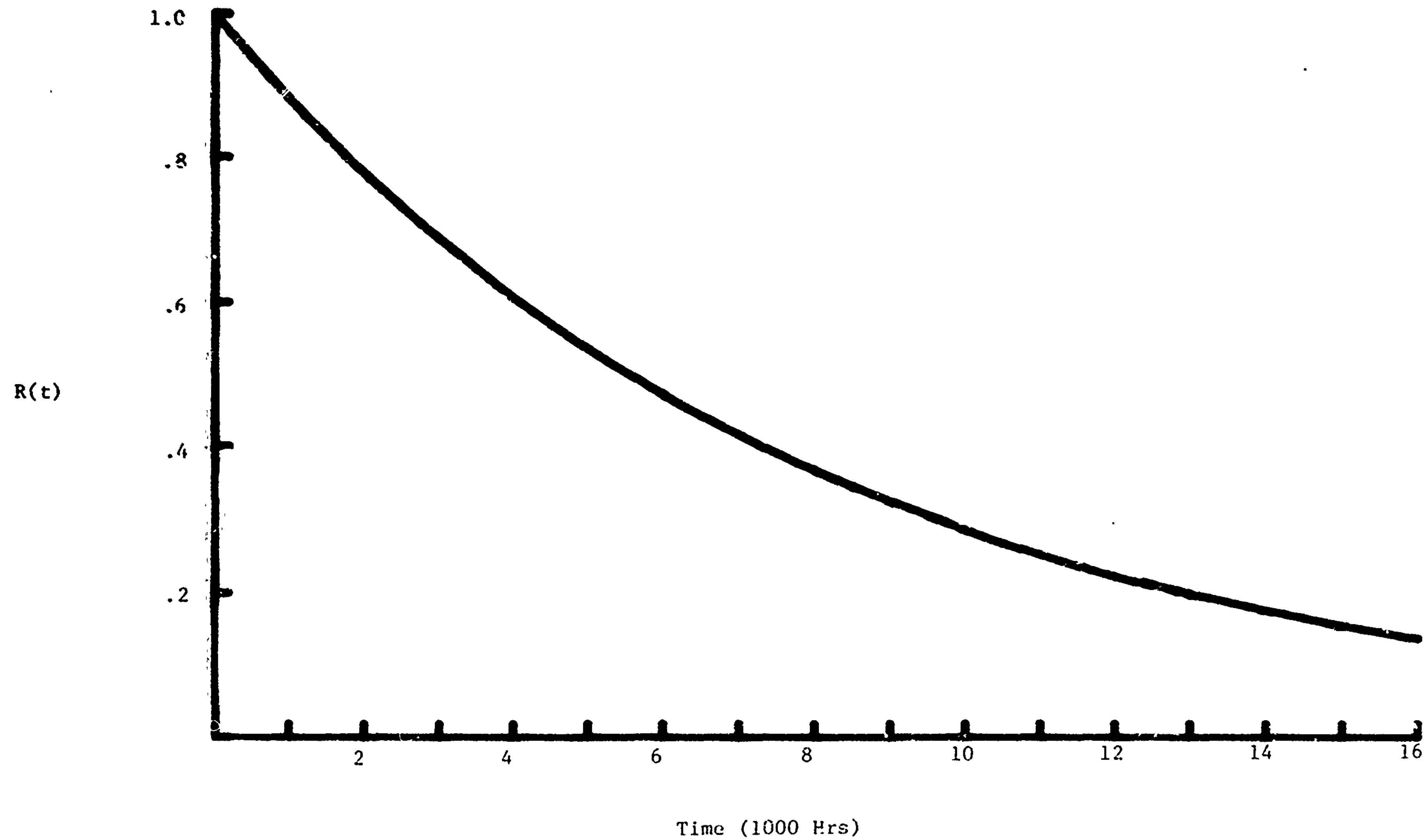


FIGURE A-62 6517 (MANUFACTURER'S DATA) MAGNETRON RELIABILITY, R(t)

(λ = 1267)

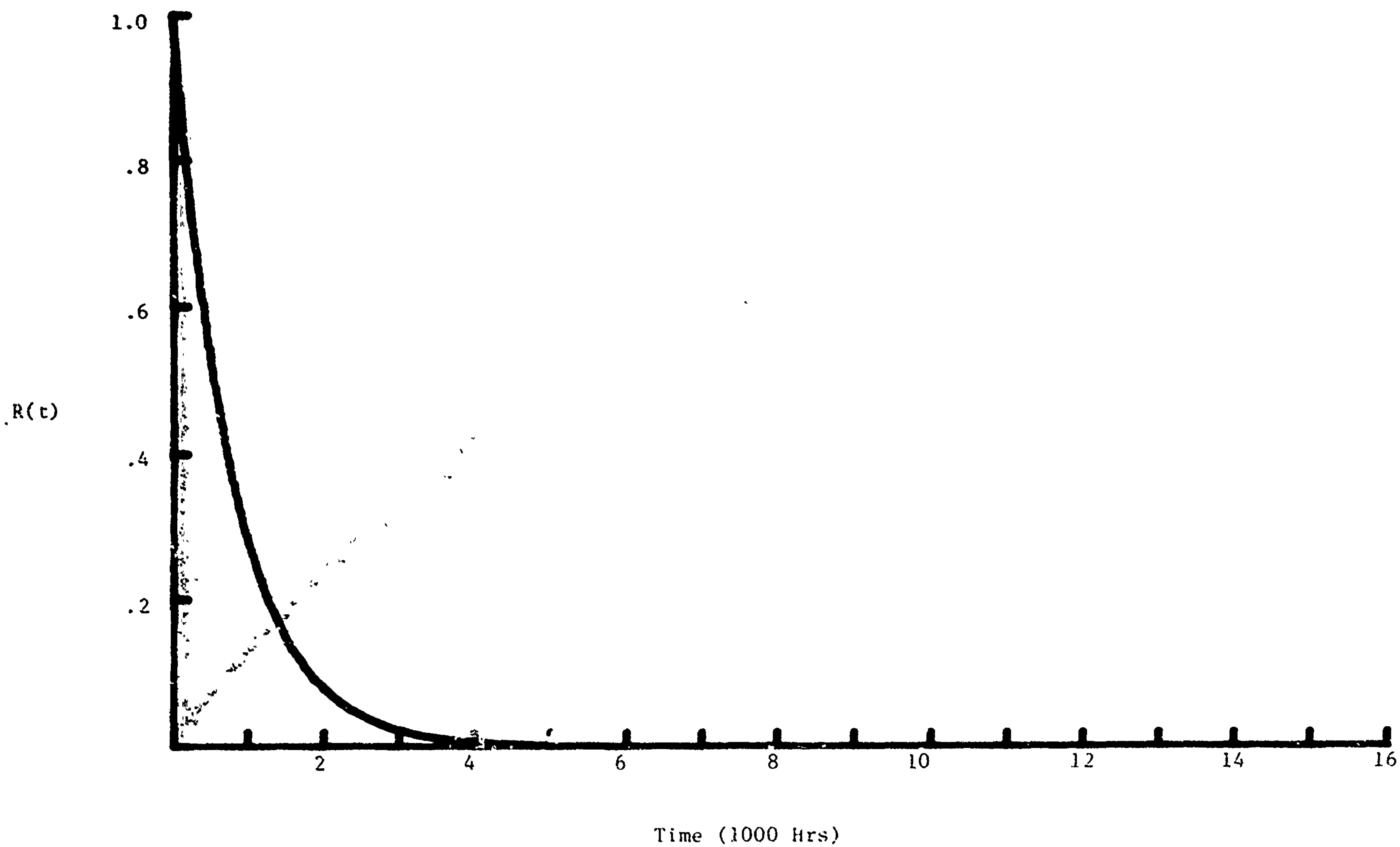


FIGURE A-63 400615 MAGNETRON RELIABILITY, R(t)

(λ = 452)

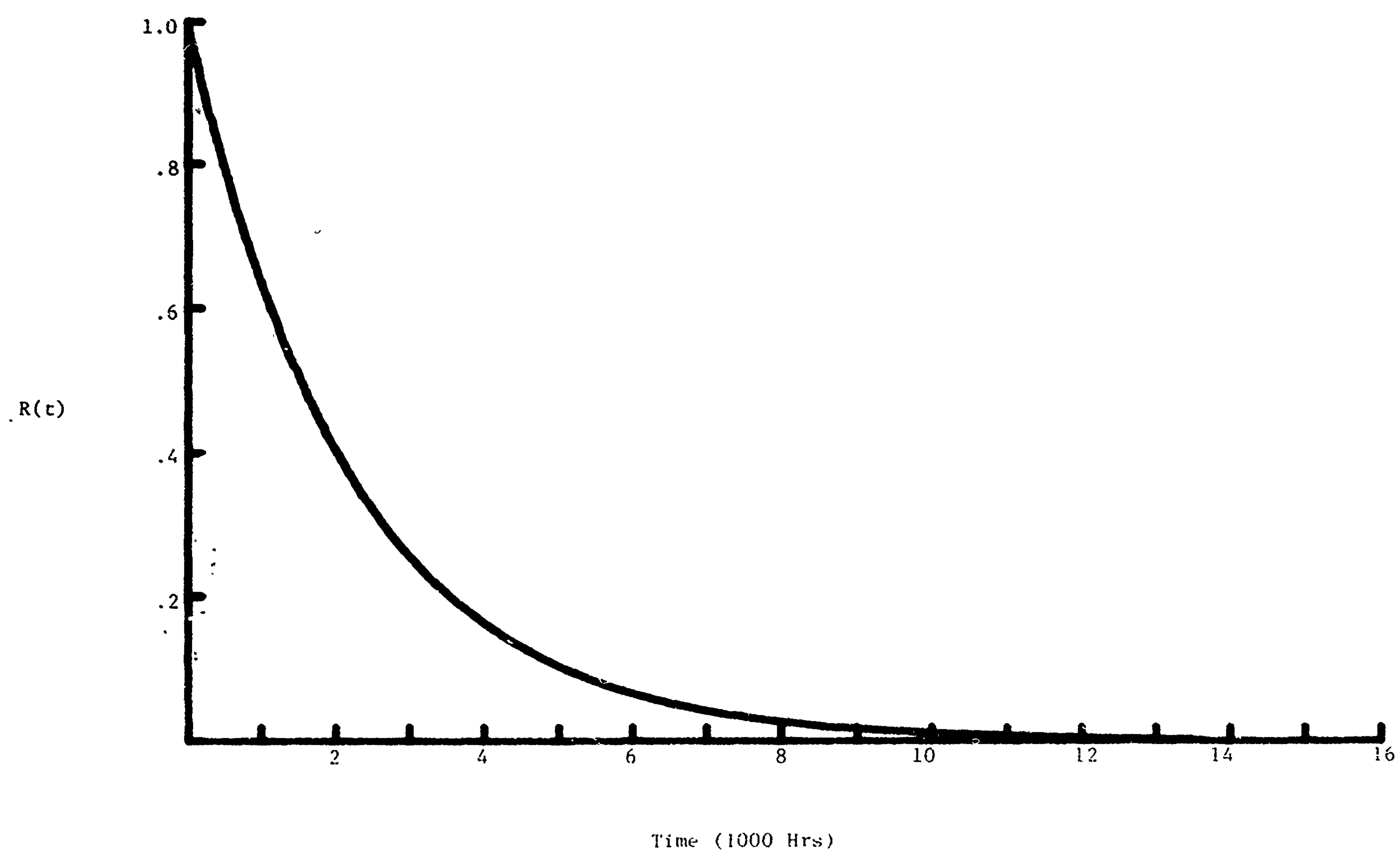


FIGURE A-64 5586 MAGNETRON RELIABILITY, R(t)

(λ = 559)

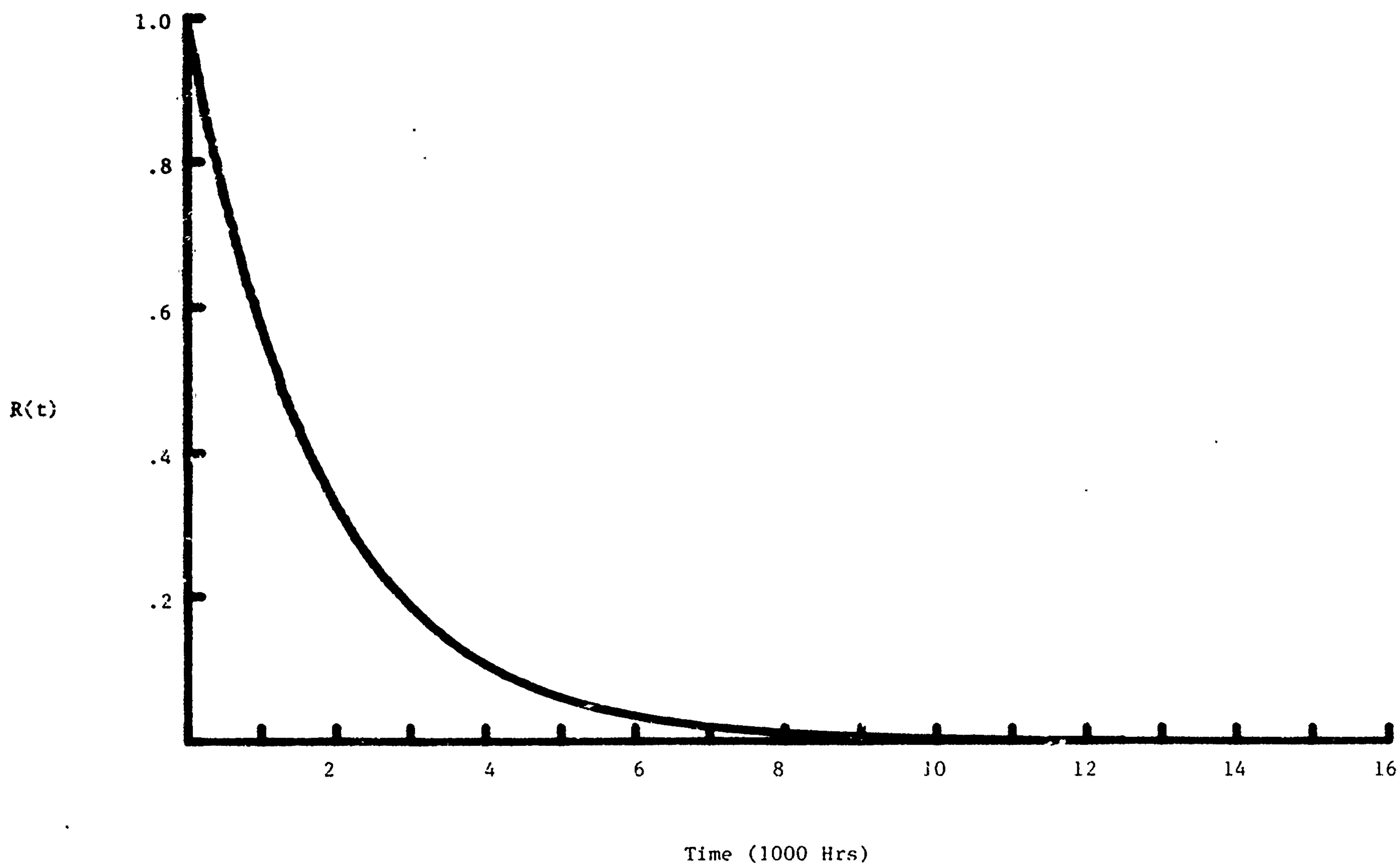


FIGURE A-65 5586 (FIXED INSTALLATION) MAGNETRON RELIABILITY, R(t)

(λ = 499)

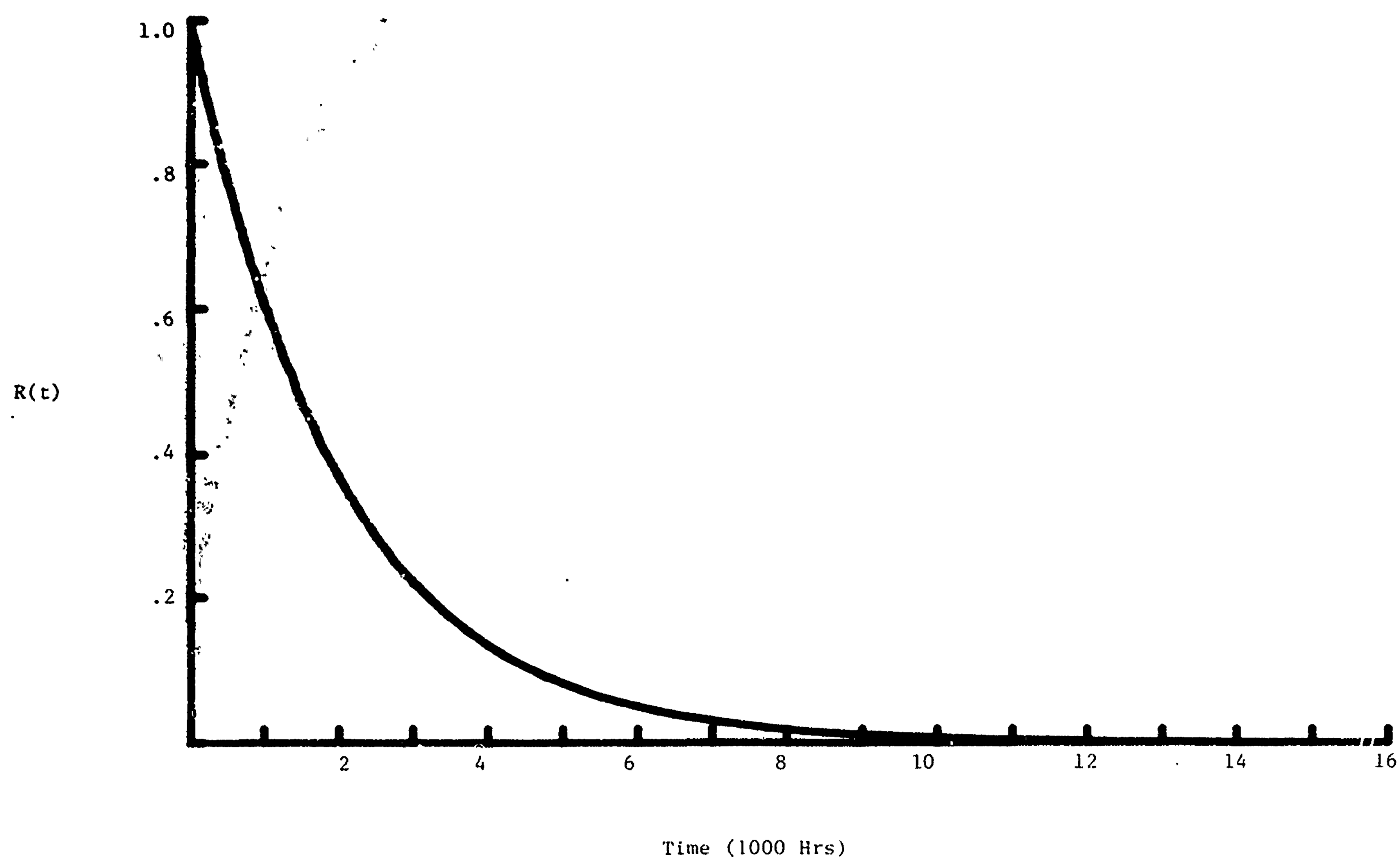


FIGURE A-66 5586 (MOBILE INSTALLATION) MAGNETRON RELIABILITY, R(t)

(λ = 669)

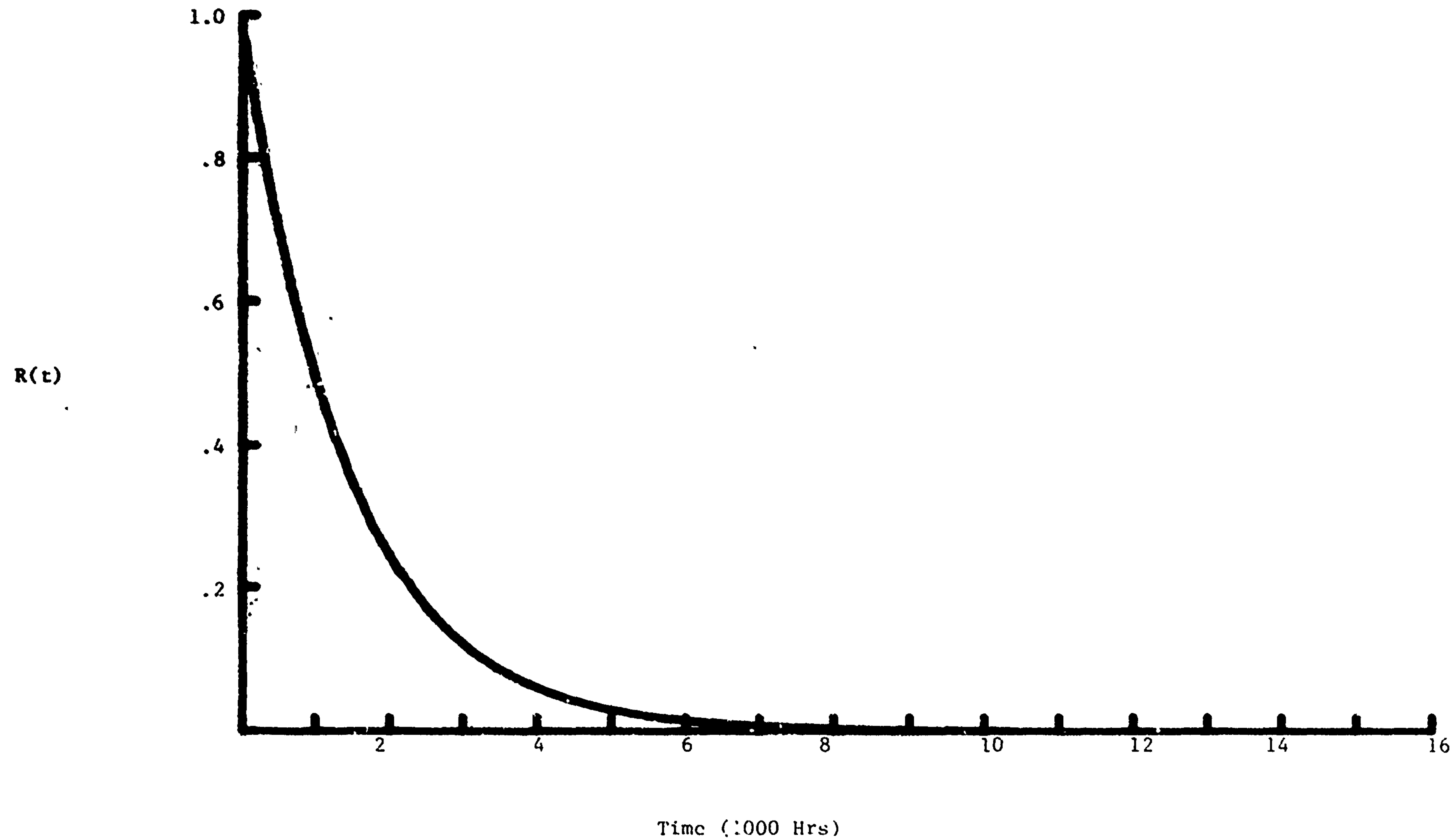


FIGURE A-67 8798 MAGNETRON RELIABILITY, R(t)

(λ = 479)

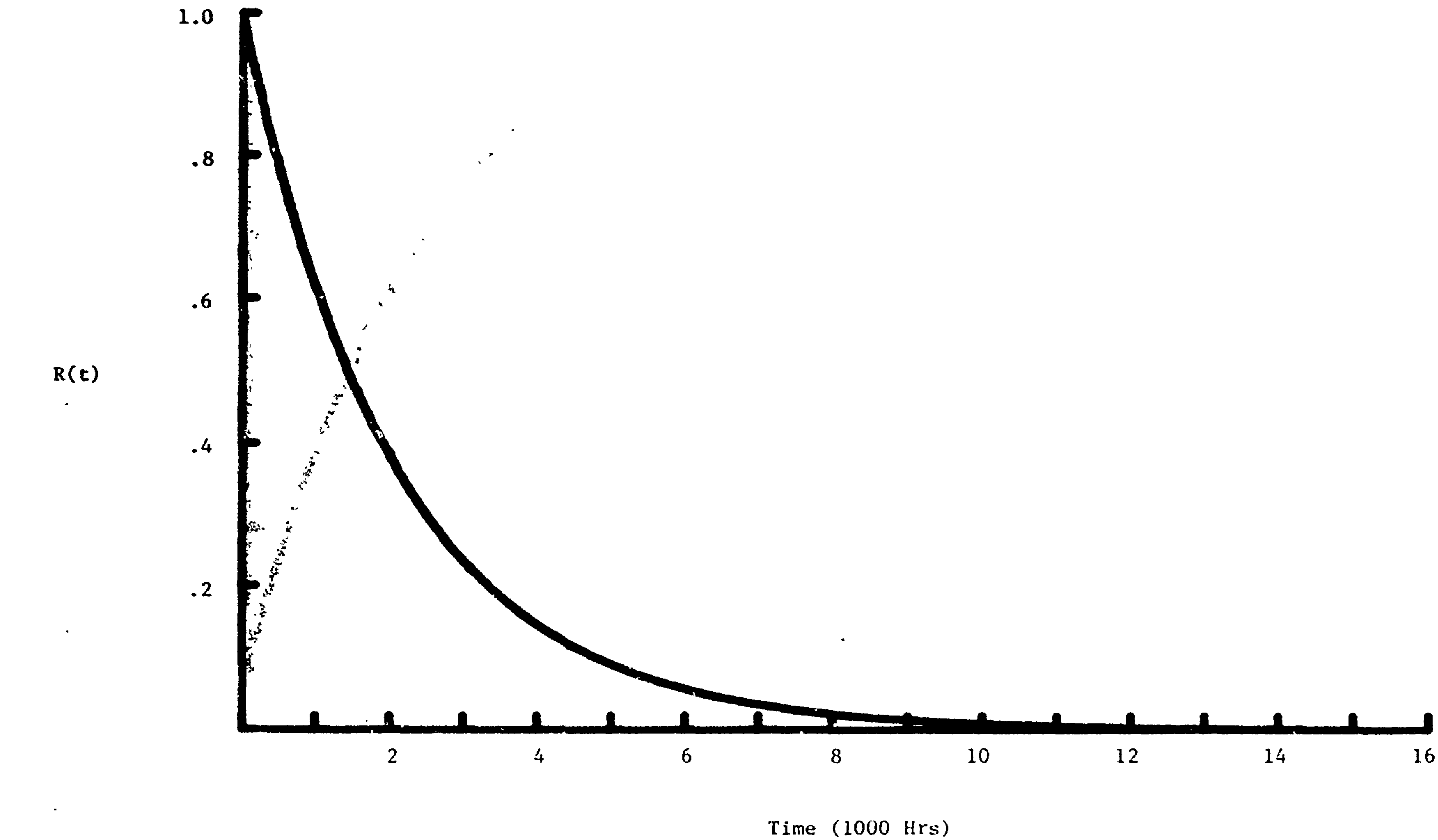


FIGURE A-68 8798 (FIXED INSTALLATION) MAGNETRON RELIABILITY, R(t)

(λ = 379)

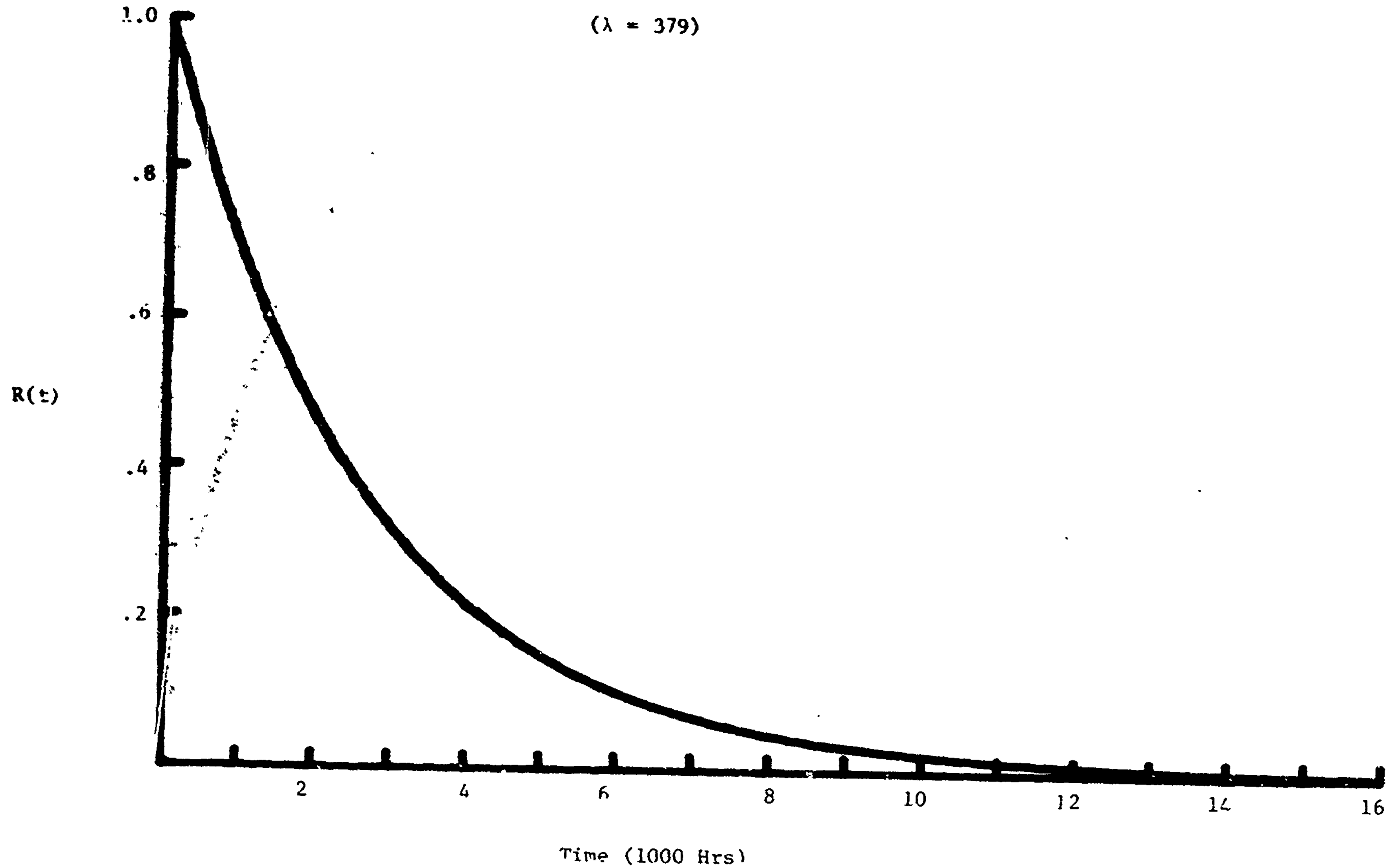


FIGURE A-69 8798 MAGNETRON (MOBILE INSTALLATION) RELIABILITY, R(t)

(λ = 464)

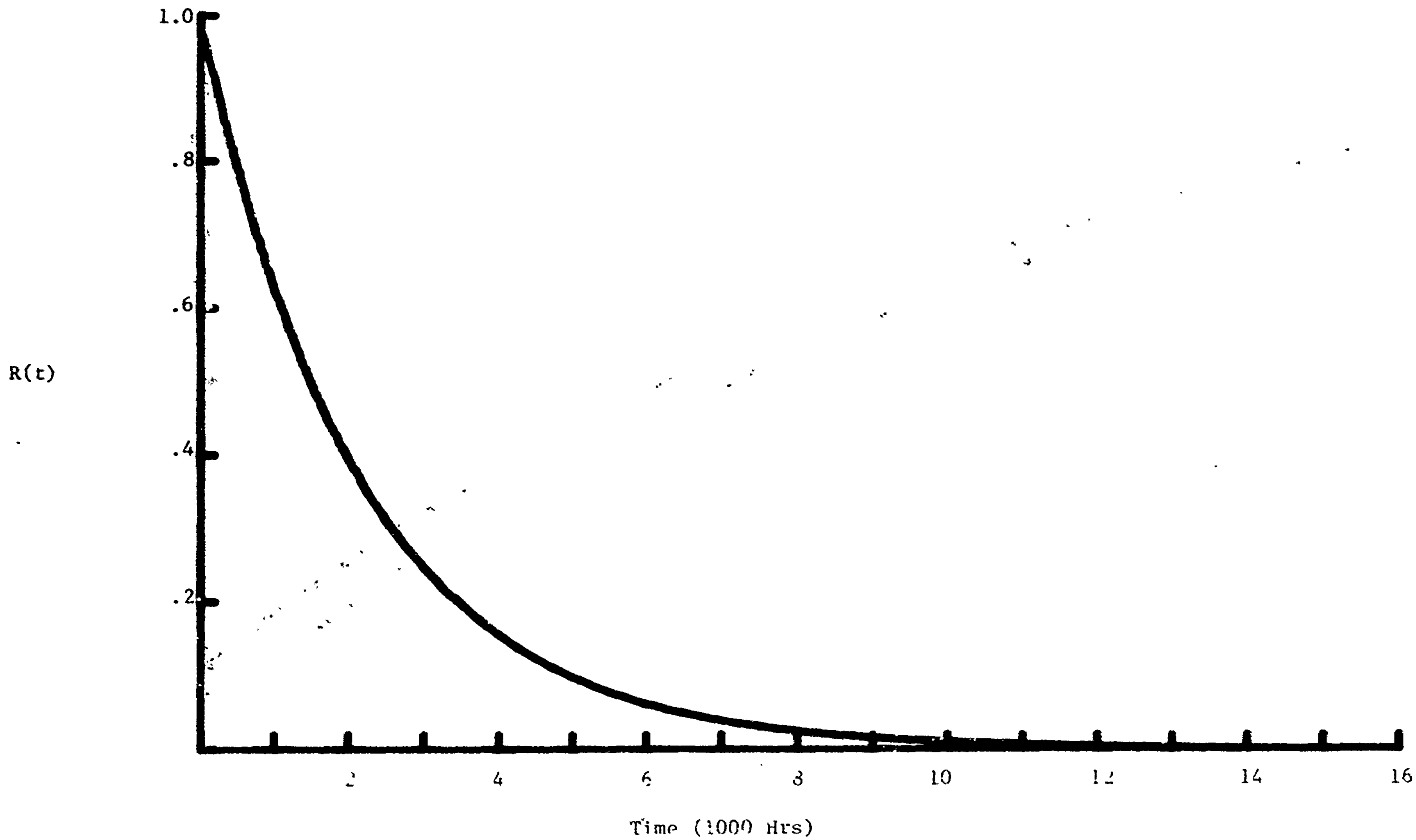


FIGURE A-70 5780 MAGNETRON RELIABILITY, R(t)

(λ = 80)

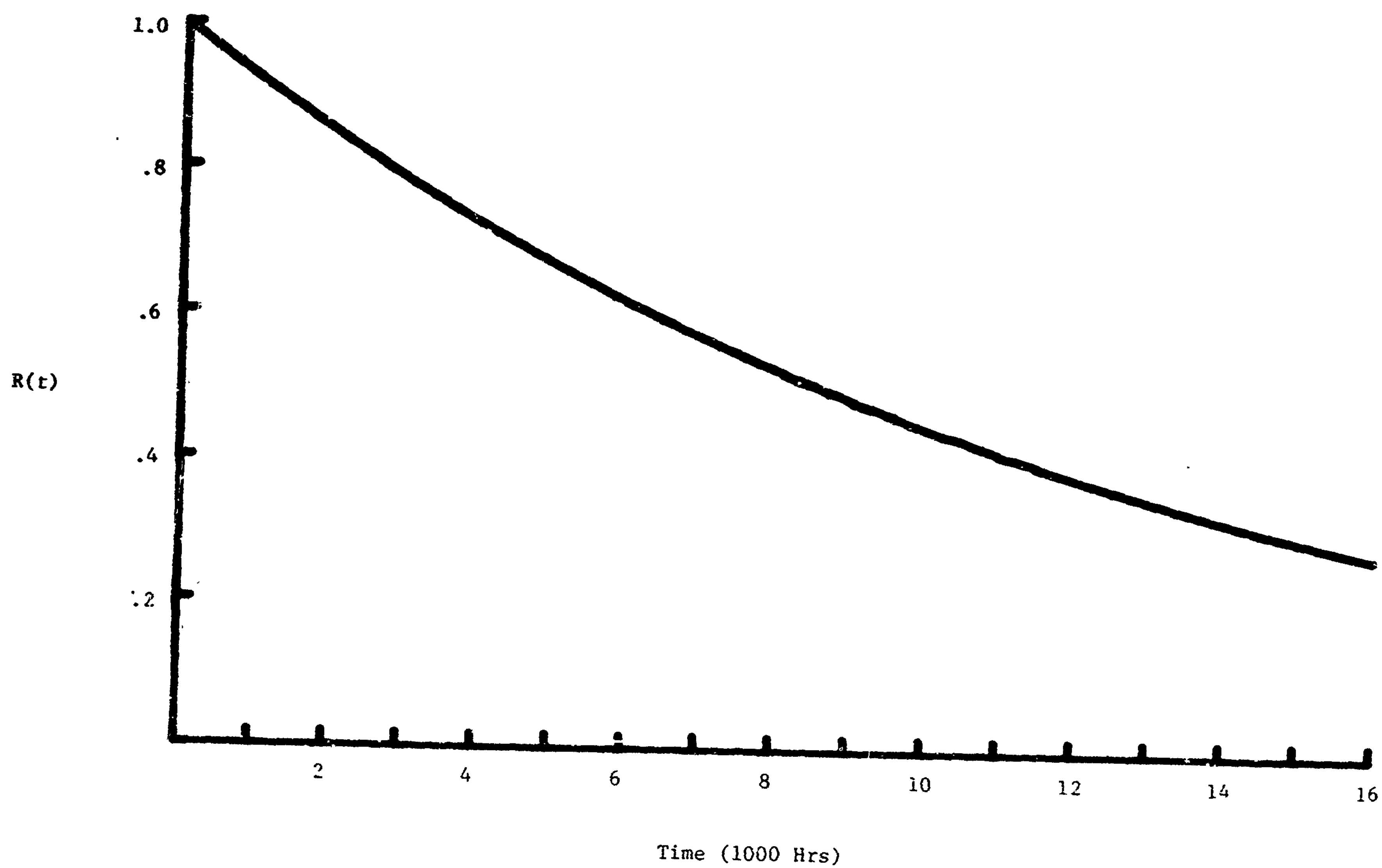


FIGURE A-71 SFD352 (MANUFACTURER'S DATA) COAXIAL MAGNETRON RELIABILITY, R(t)

(λ = 263)

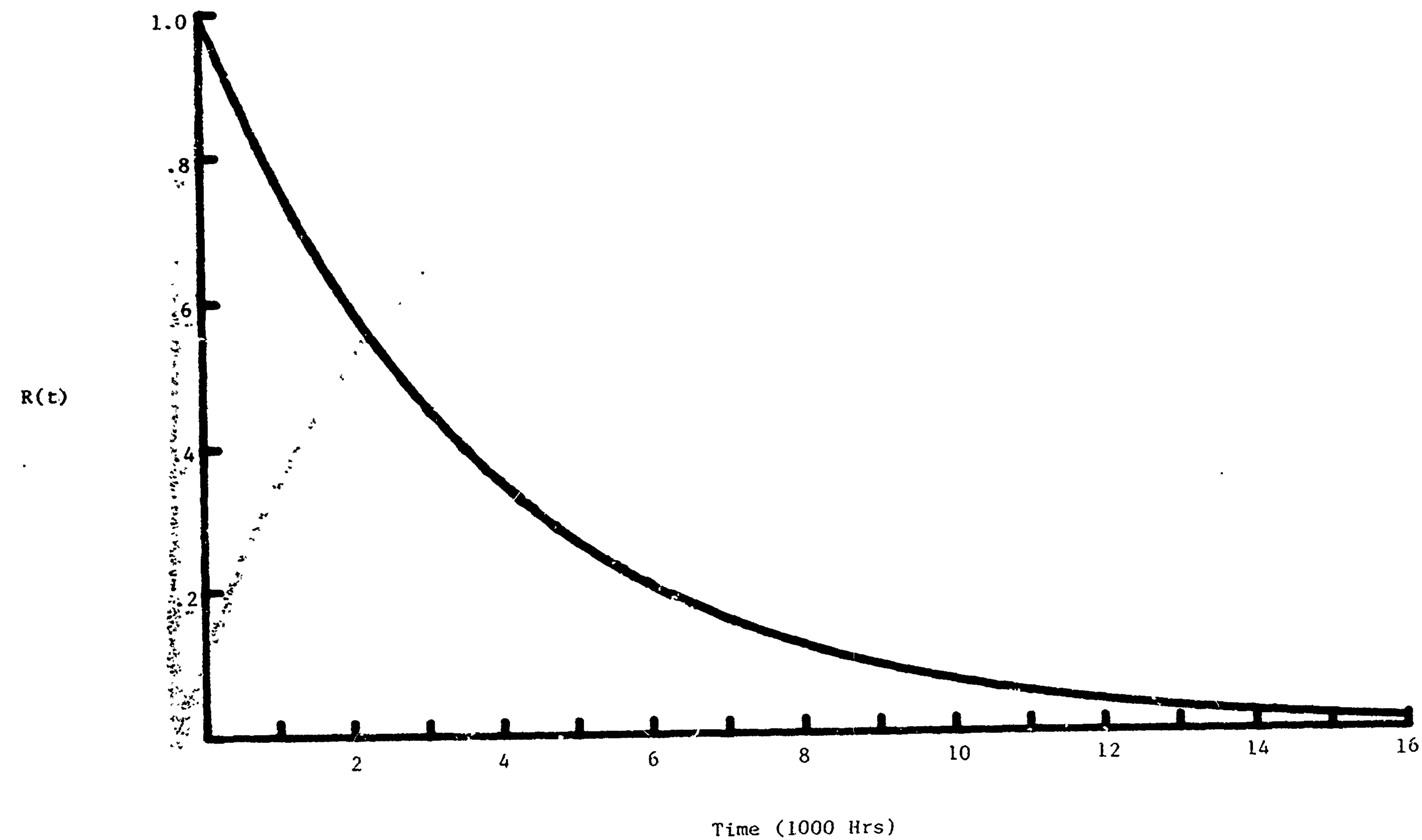


FIGURE A-72 6344 (MANUFACTURER'S DATA) MAGNETRON RELIABILITY
(λ = 335)

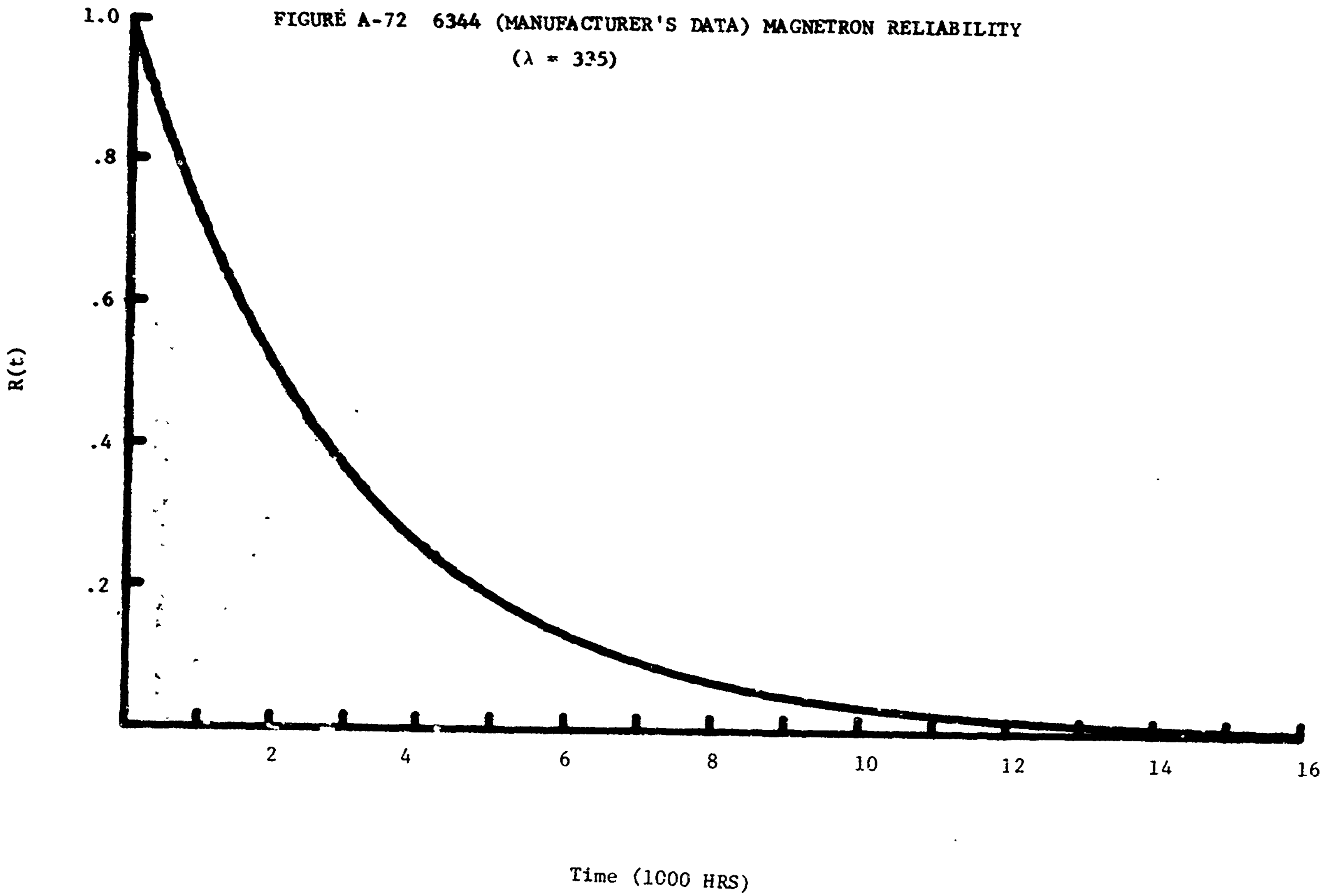


FIGURE A-73 SFD370 (MANUFACTURER'S DATA) COAXIAL MAGNETRON RELIABILITY, R(t)

(λ = 105)

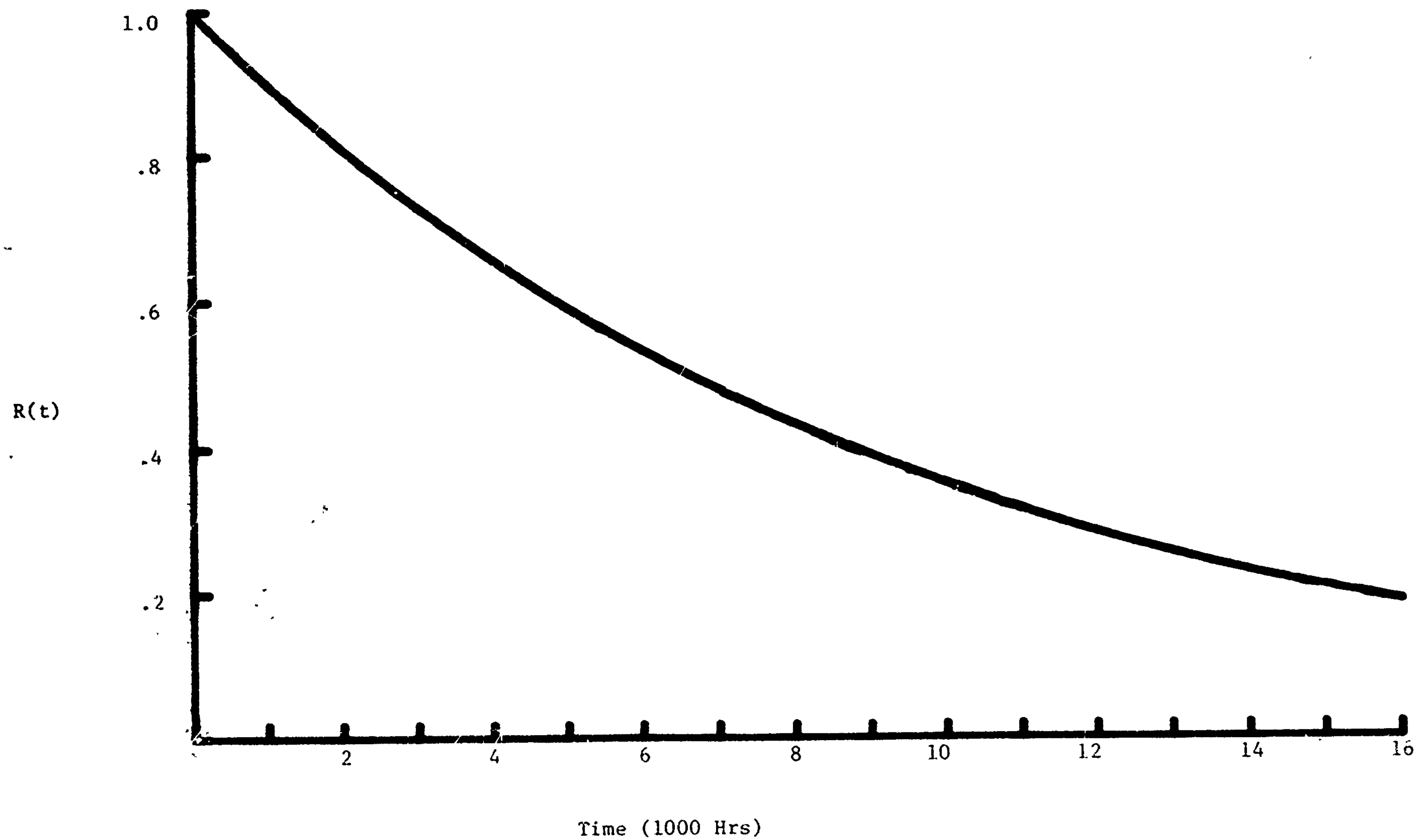


FIGURE A-74 SFD377A (MANUFACTURER'S DATA) COAXIAL MAGNETRON RELIABILITY, R(t)

(λ = 200)

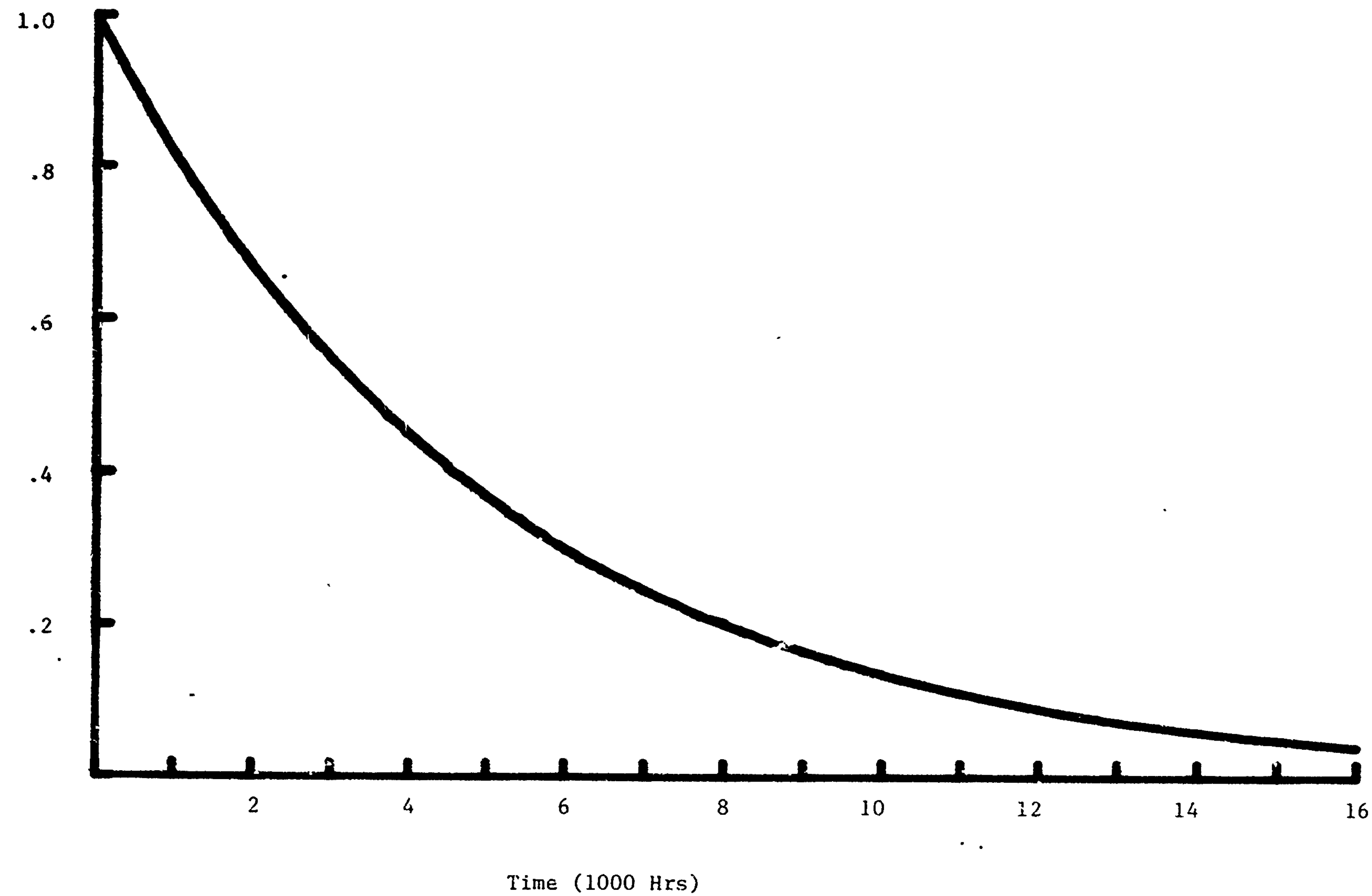


FIGURE A-75 SFD342 (MANUFACTURER'S DATA) COAXIAL MAGNETRON RELIABILITY, R(t)

(λ = 55)

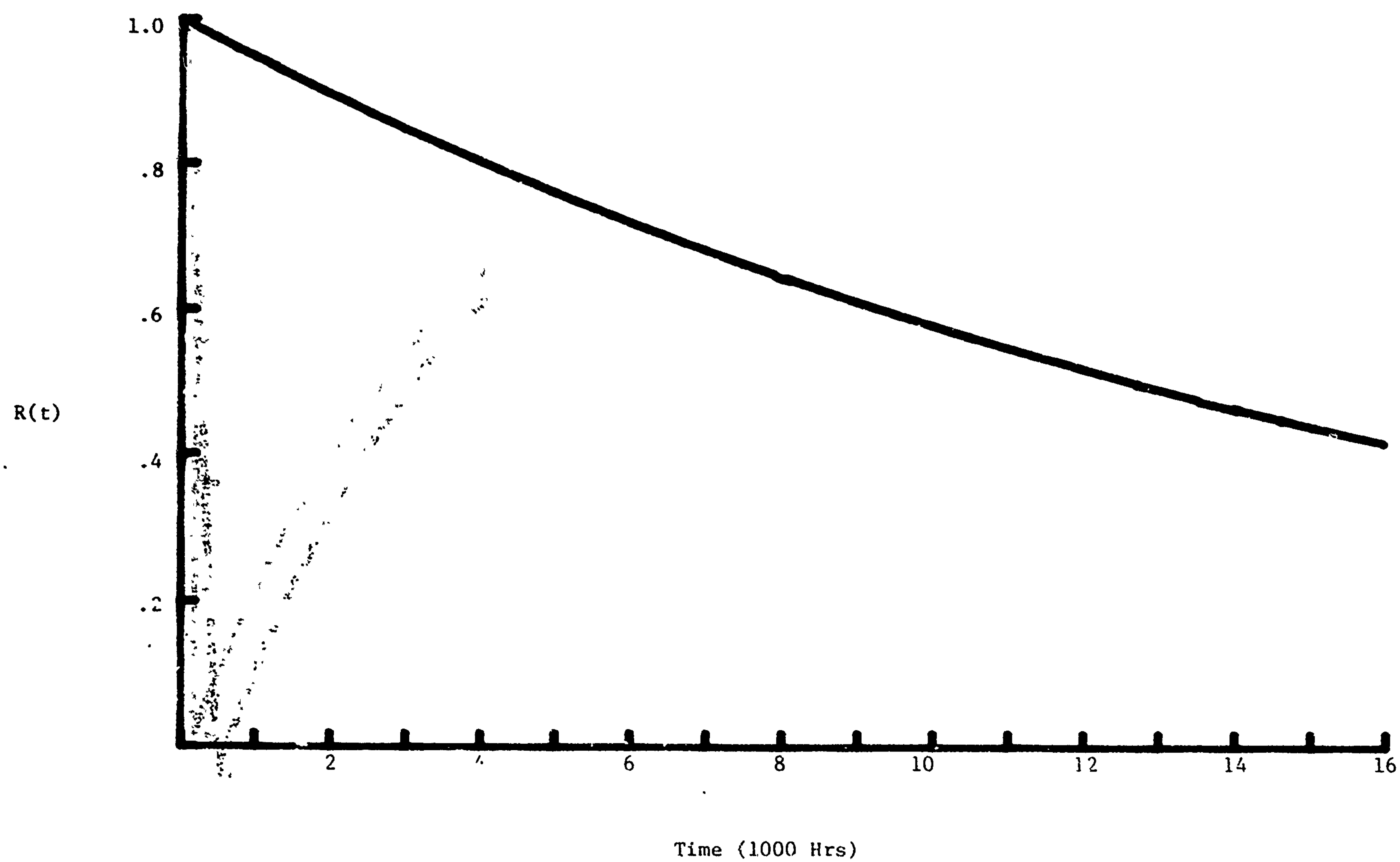


FIGURE A-76 7452 (MANUFACTURER'S DATA) MAGNETRON RELIABILITY, R(t)

(λ = 263)

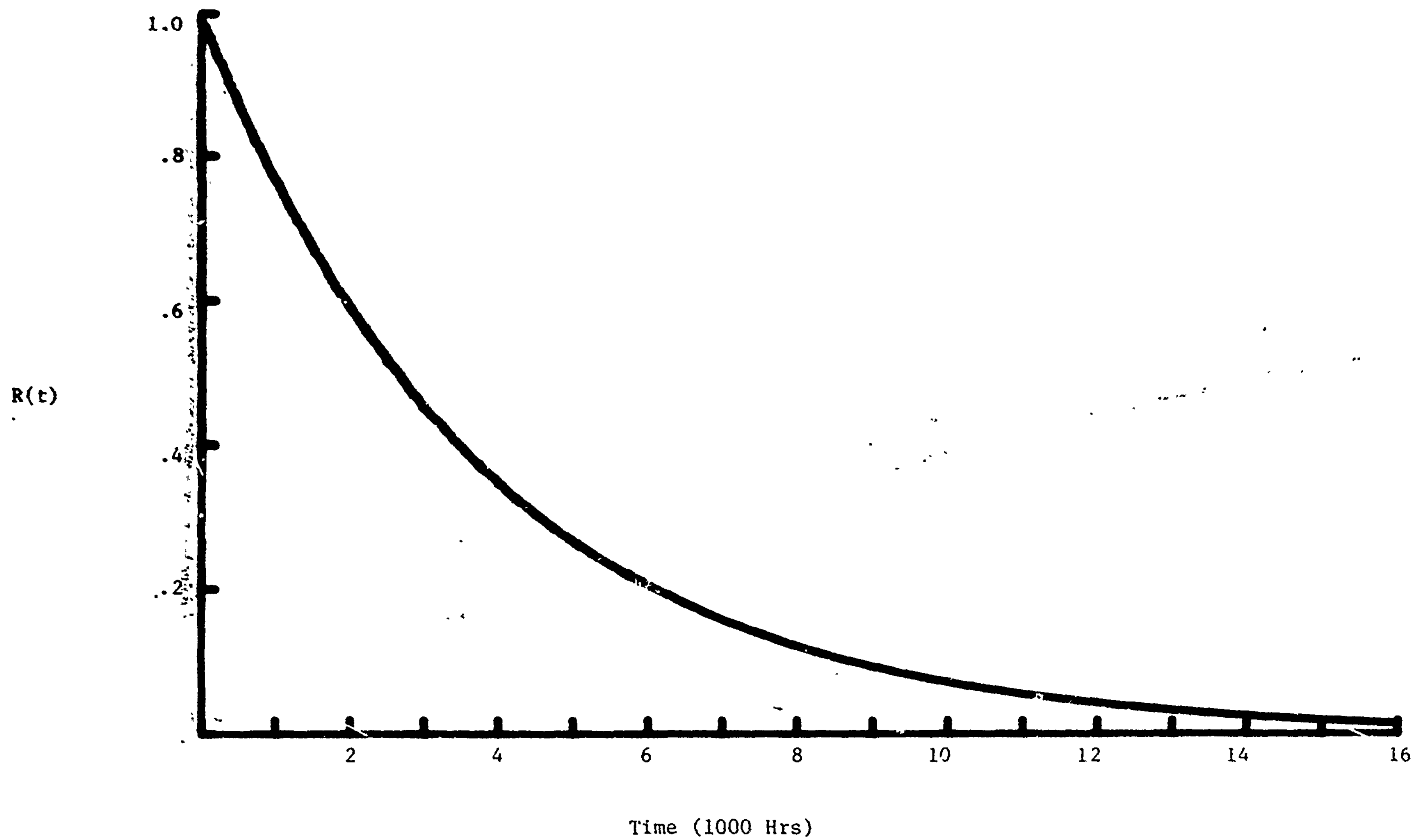


FIGURE A-77 BLM198 MAGNETRON RELIABILITY, R(t)

(λ = 213)

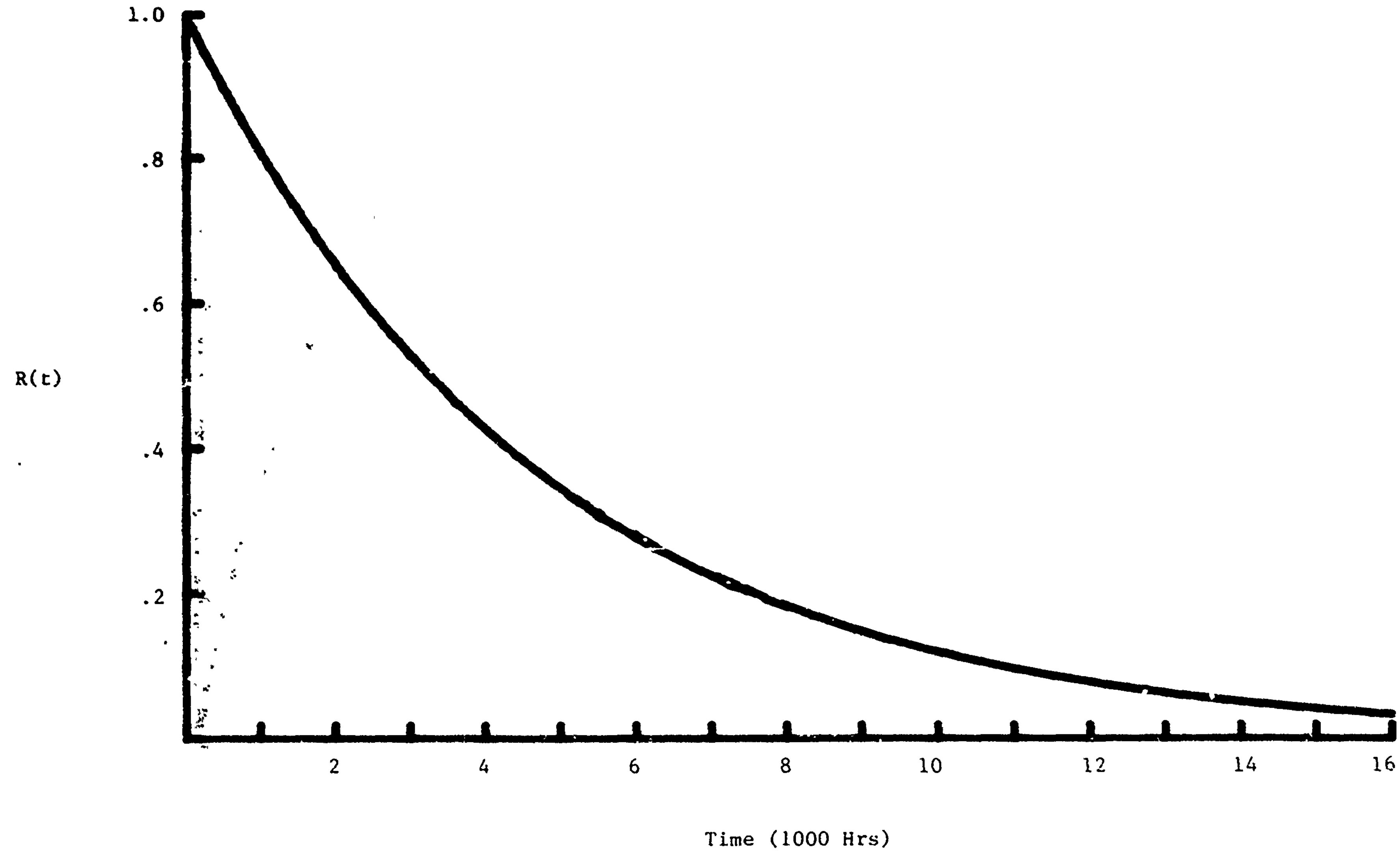


FIGURE A-78 7256 MAGNETRON RELIABILITY, R(t)

(λ = 533)

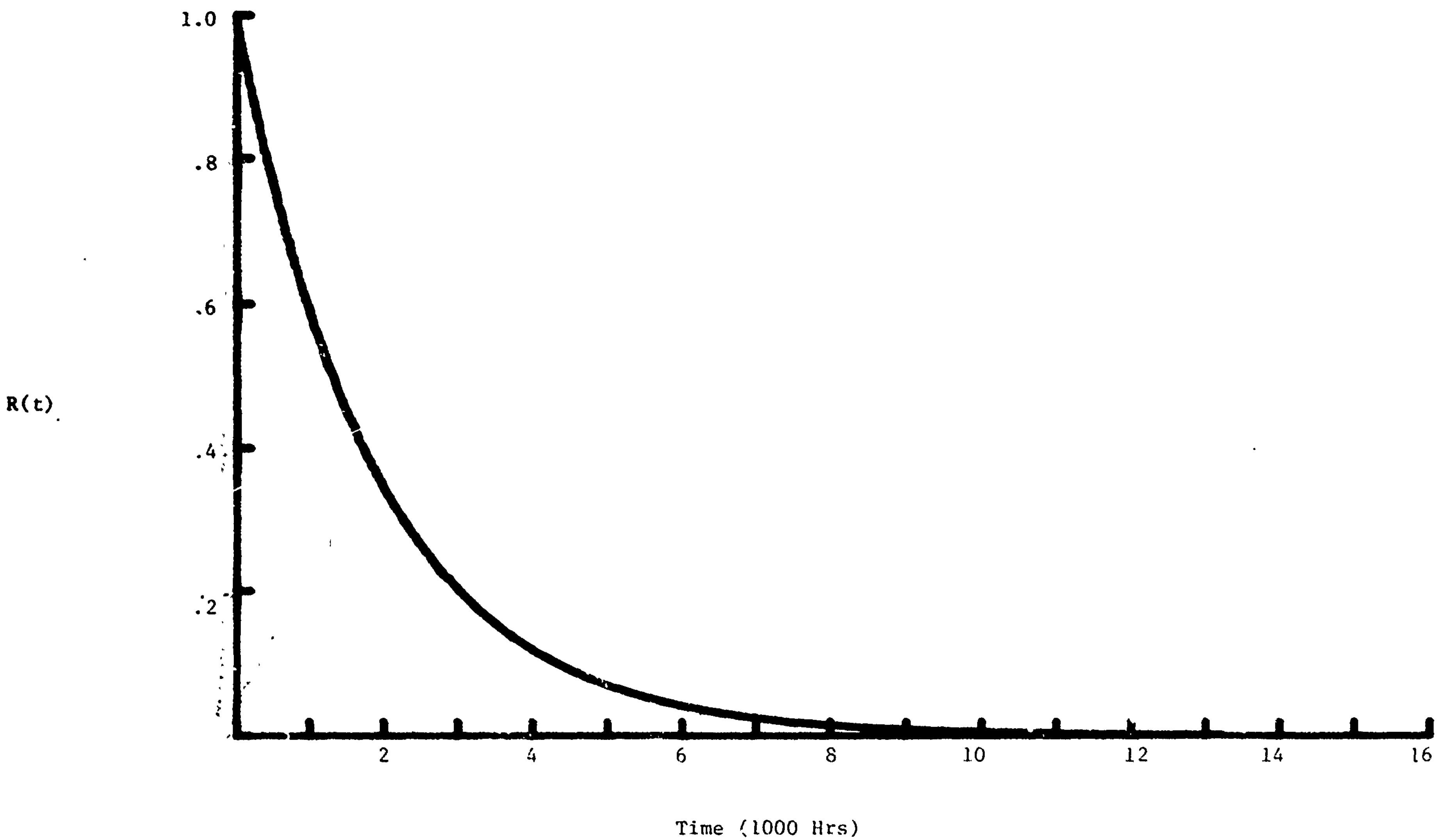


FIGURE A-79 7256 (MANUFACTURER'S DATA) MAGNETRON RELIABILITY, R(t)

(λ = 159)

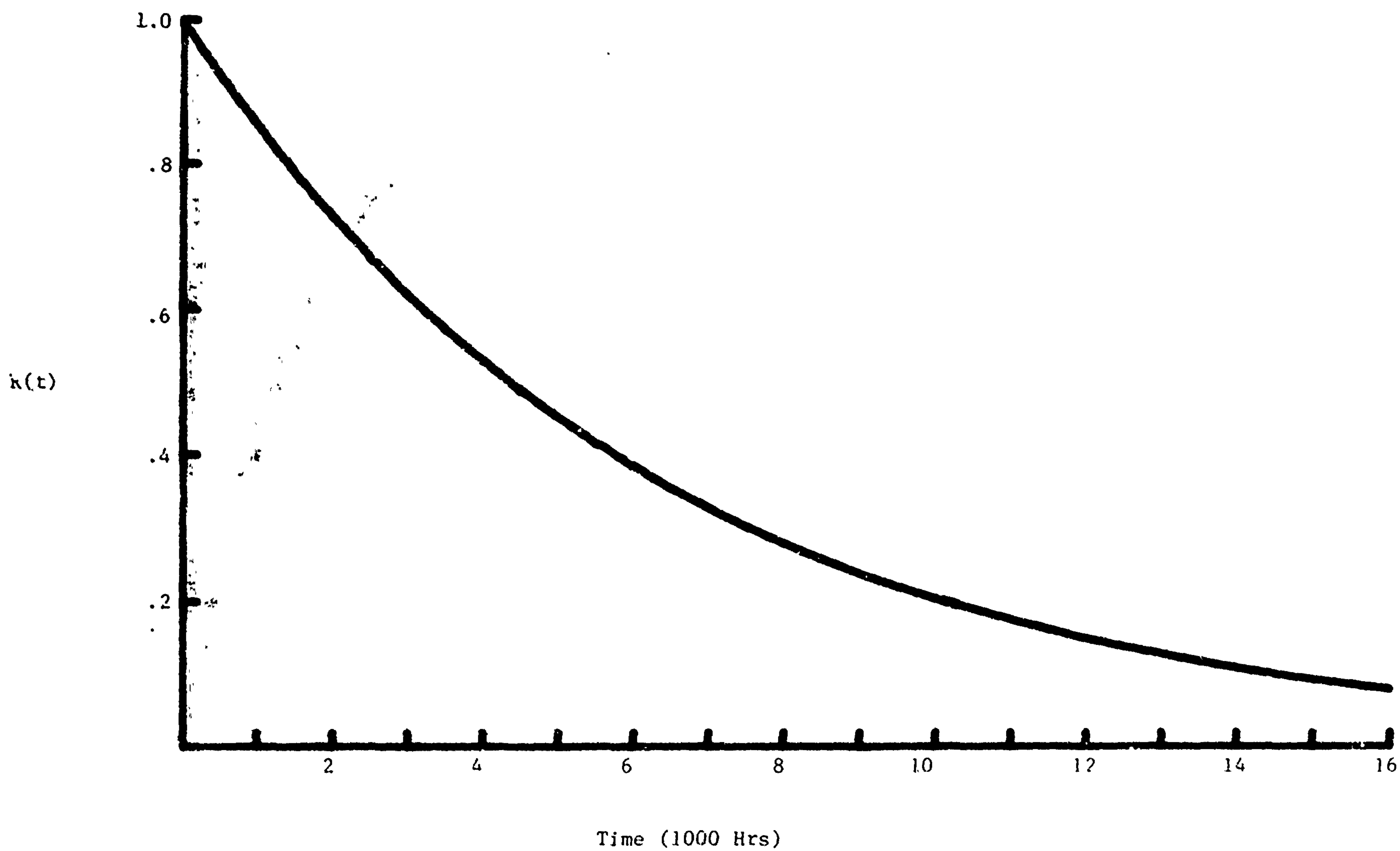


FIGURE A-80 7256 (FIXED INSTALLATION) MAGNETRON RELIABILITY, R(t)

(λ = 520)

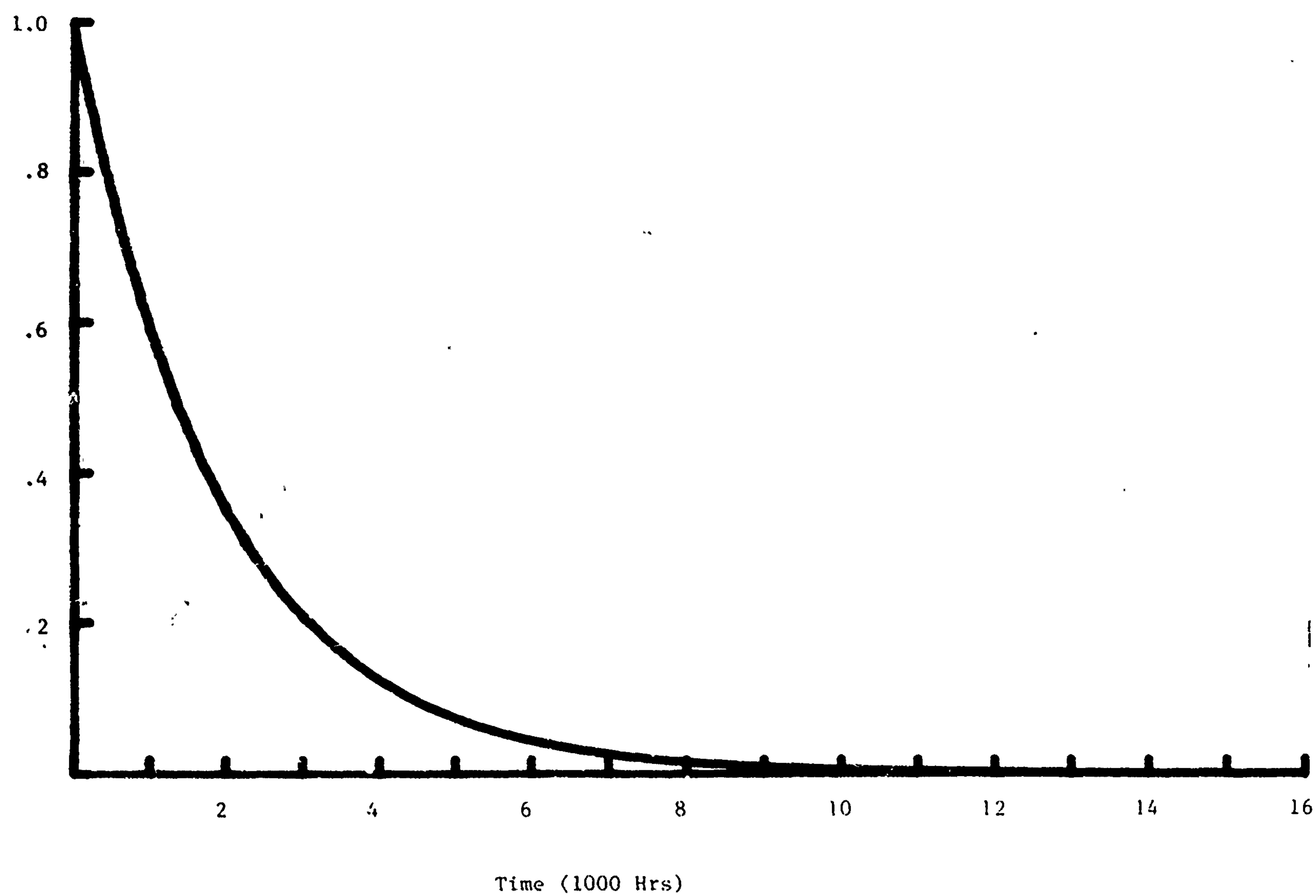


FIGURE A-81 7256 (MOBILE INSTALLATION) MAGNETRON RELIABILITY, R(t)

(λ = 554)

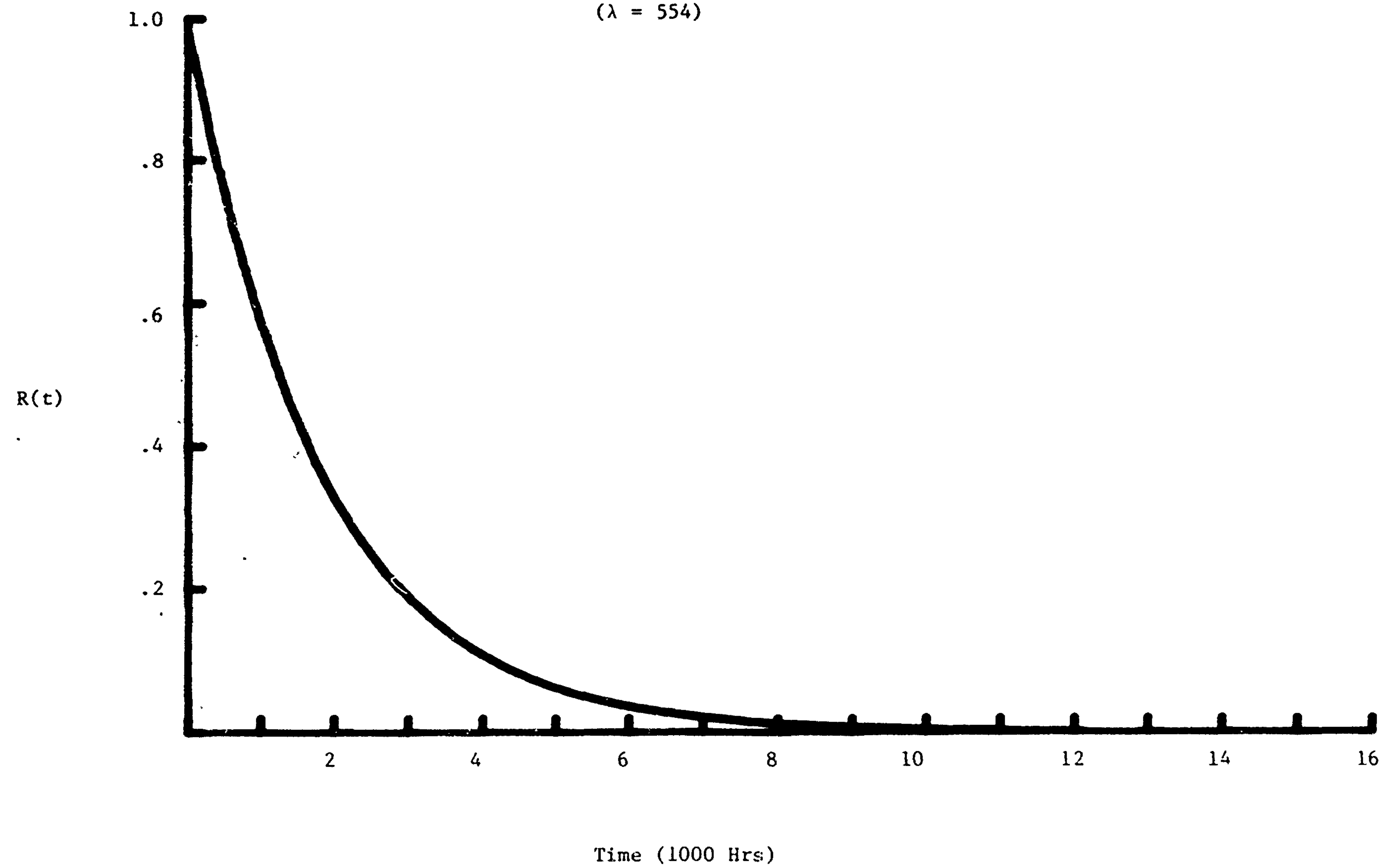


FIGURE A-82 2J55 (MANUFACTURER'S DATA) MAGNETRON RELIABILITY

(λ = 366

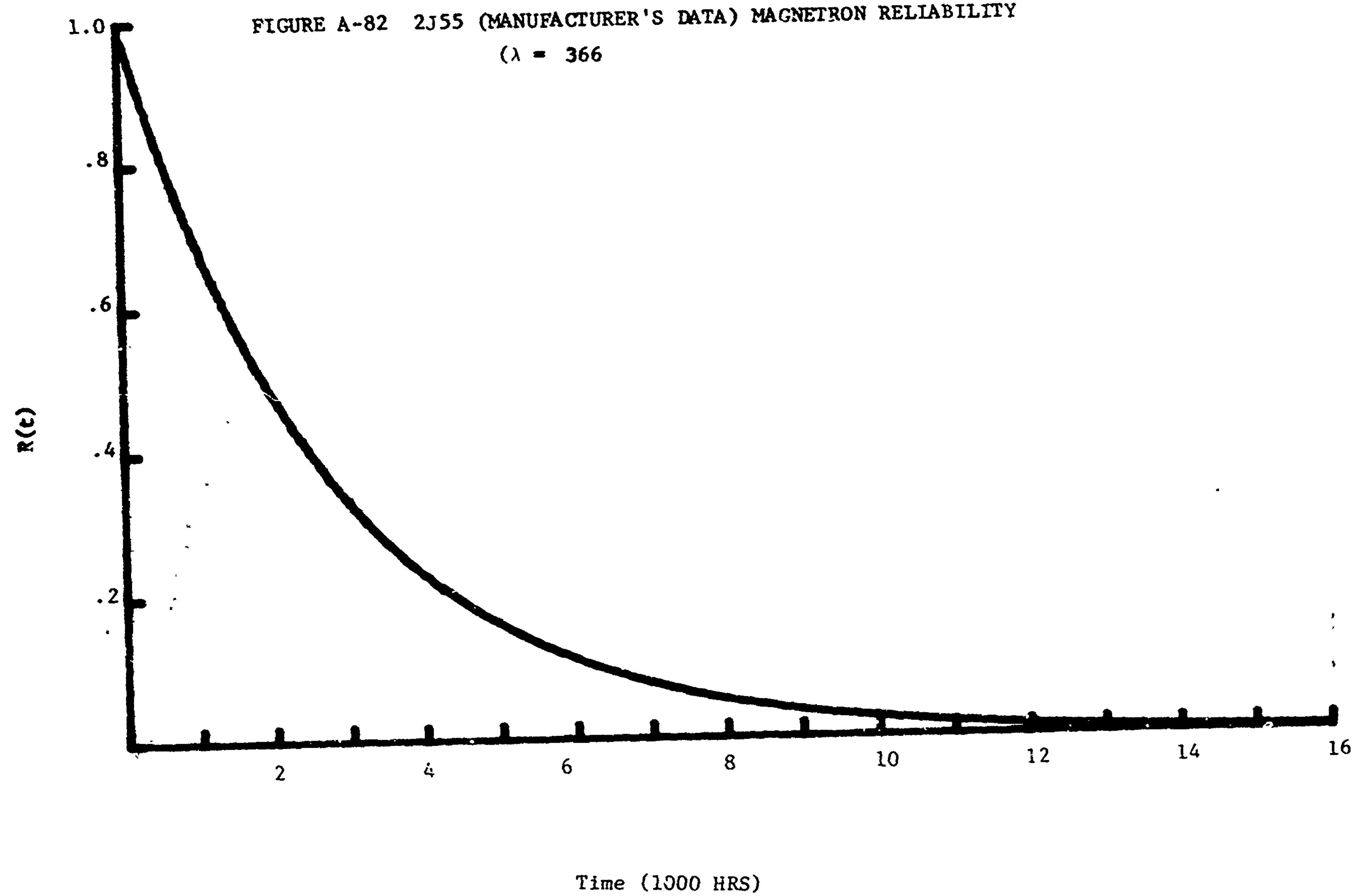


FIGURE A-83 VA913A KLYSTRON RELIABILITY, R(t)

(λ = 225)

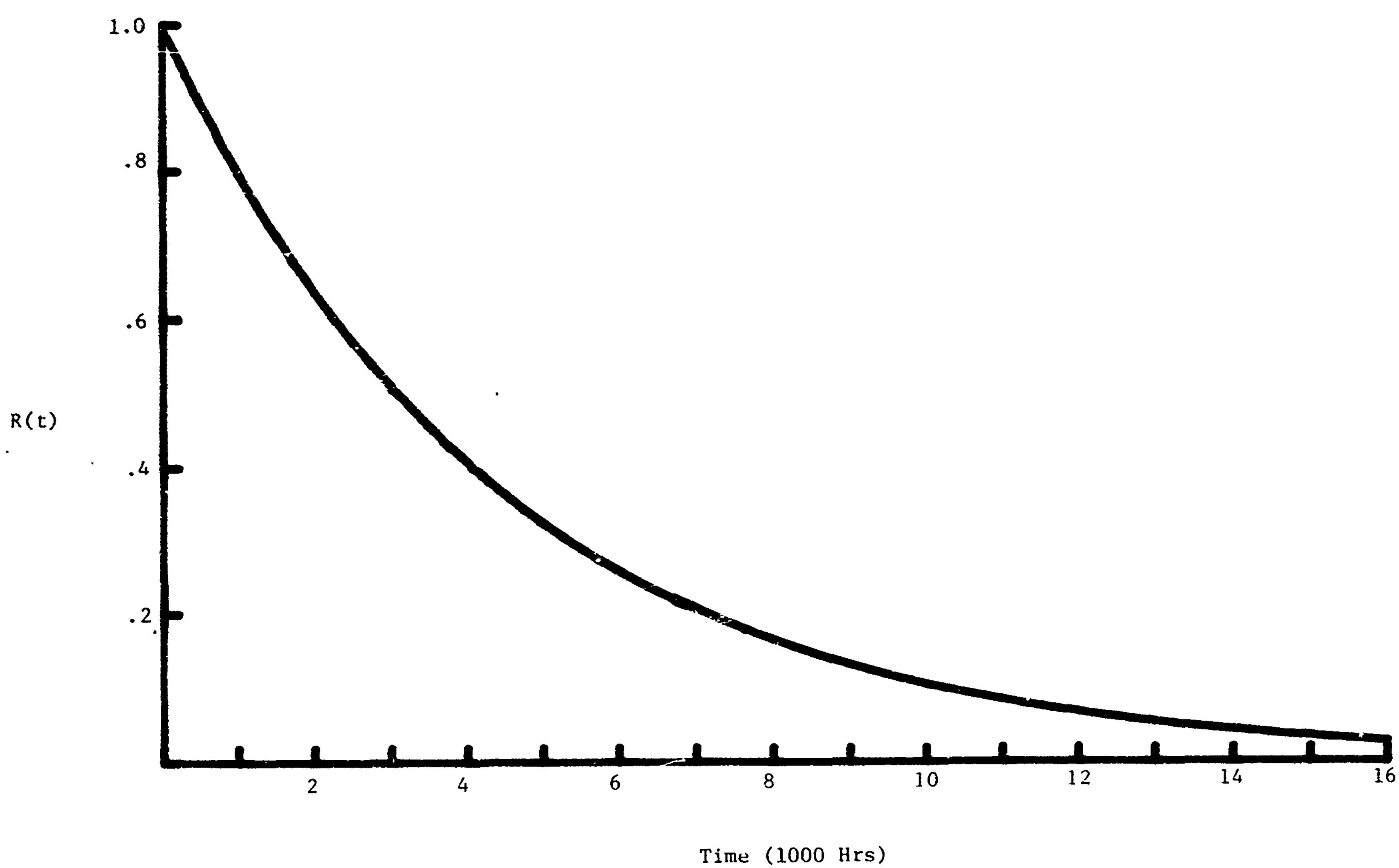


Figure A-84 VA154H TWYSTRON RELIABILITY R(t)

(λ = 487)

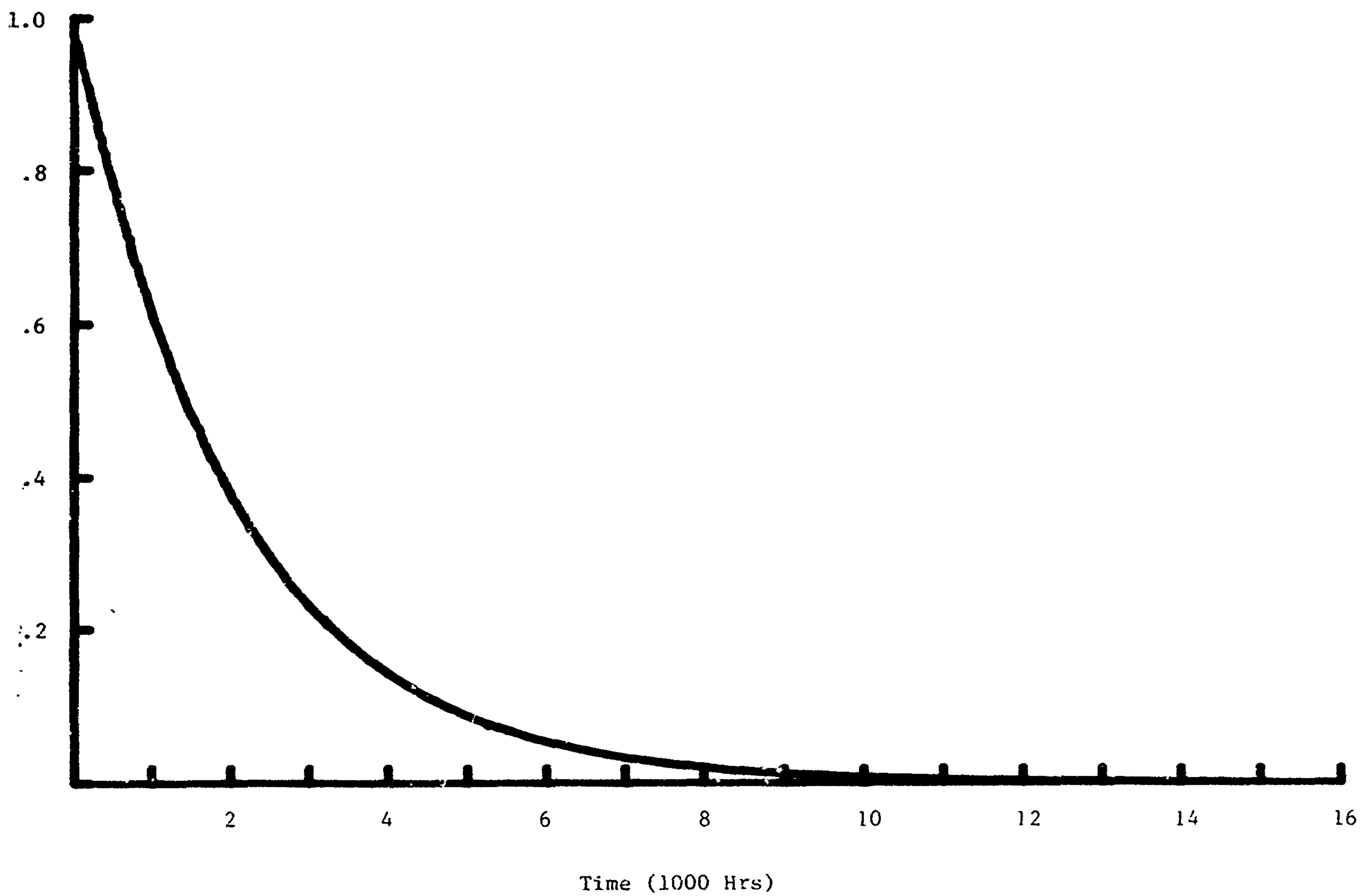


Figure A-85 VA145E TWYSTRON RELIABILITY, R(t)

(λ = 449)

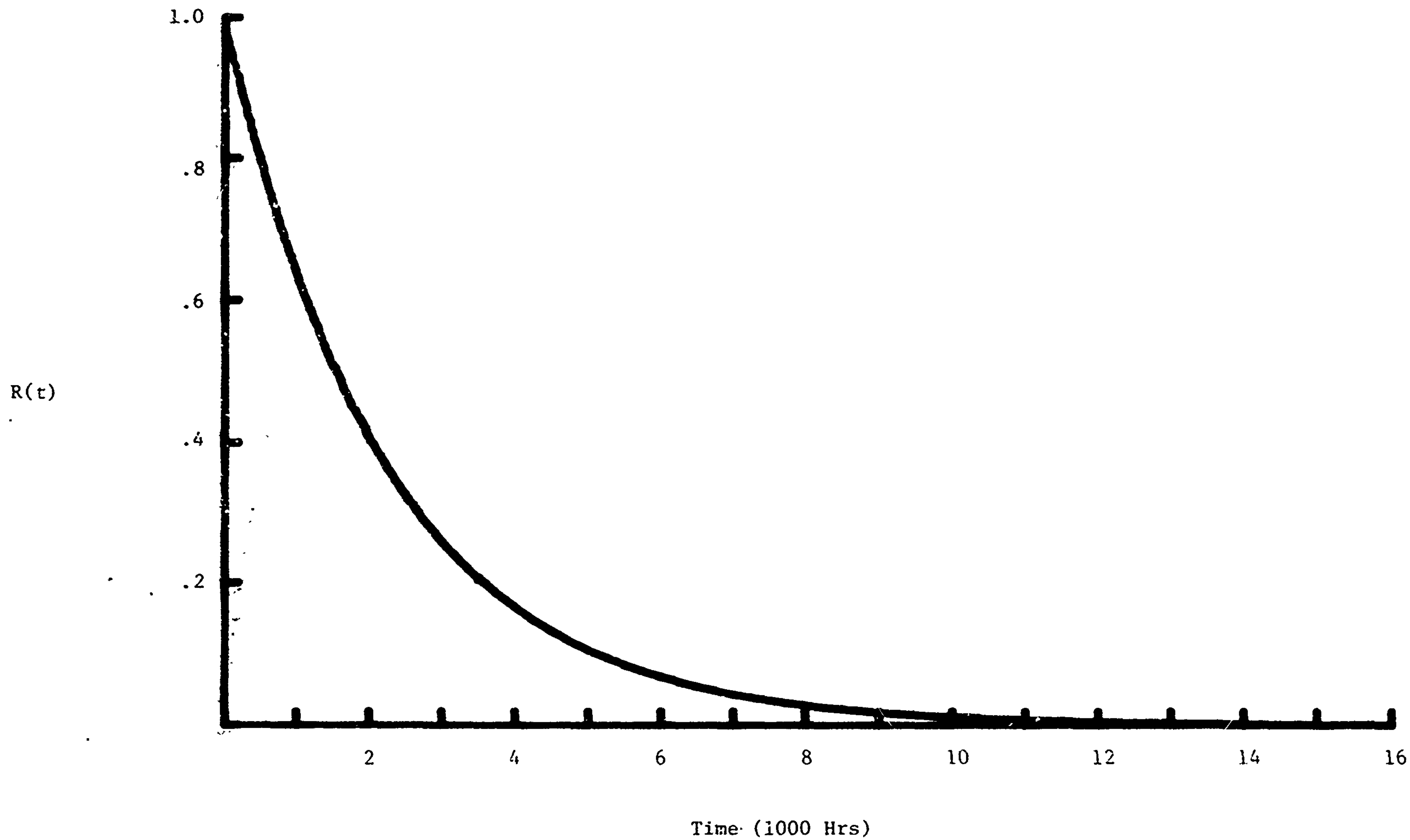


Figure A-86 VA144 TWYSTRON RELIABILITY, R(t)

(λ = 847)

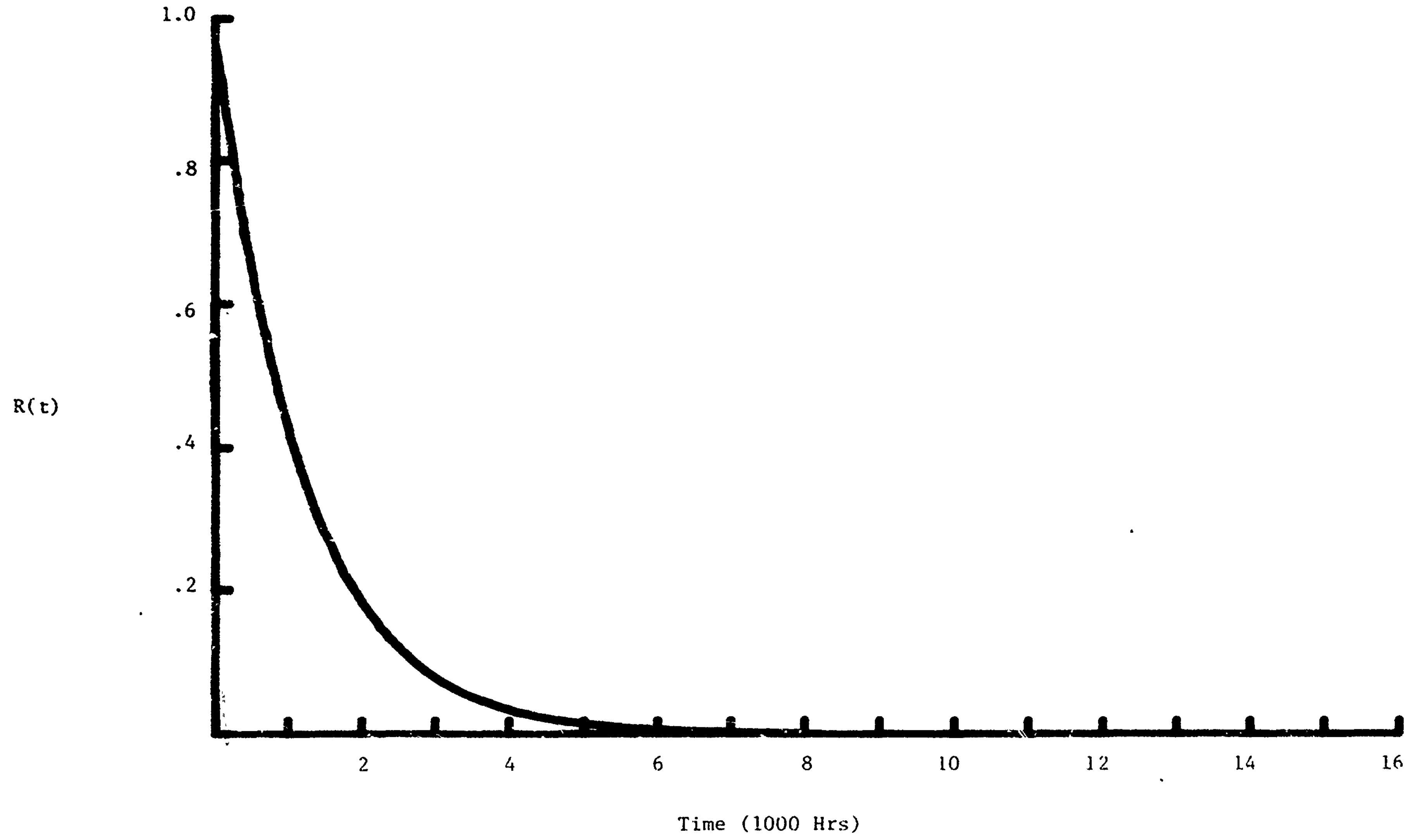


Figure A-87 7835 GRIDDED TUBE RELIABILITY, R(t)

(λ = 136)

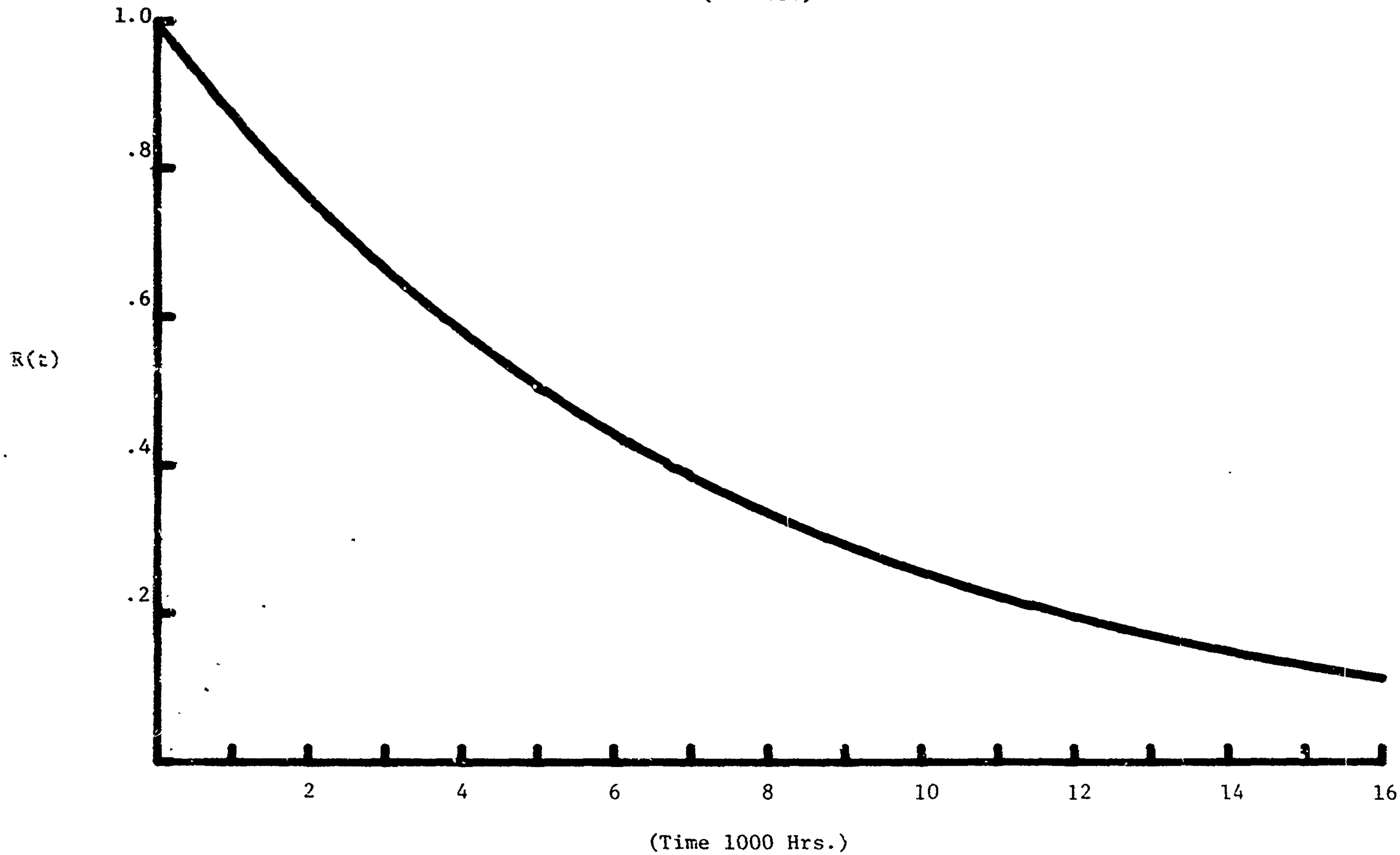


Figure A-88 2041 GRIDDED TUBE RELIABILITY, R(t)

(λ = 142)

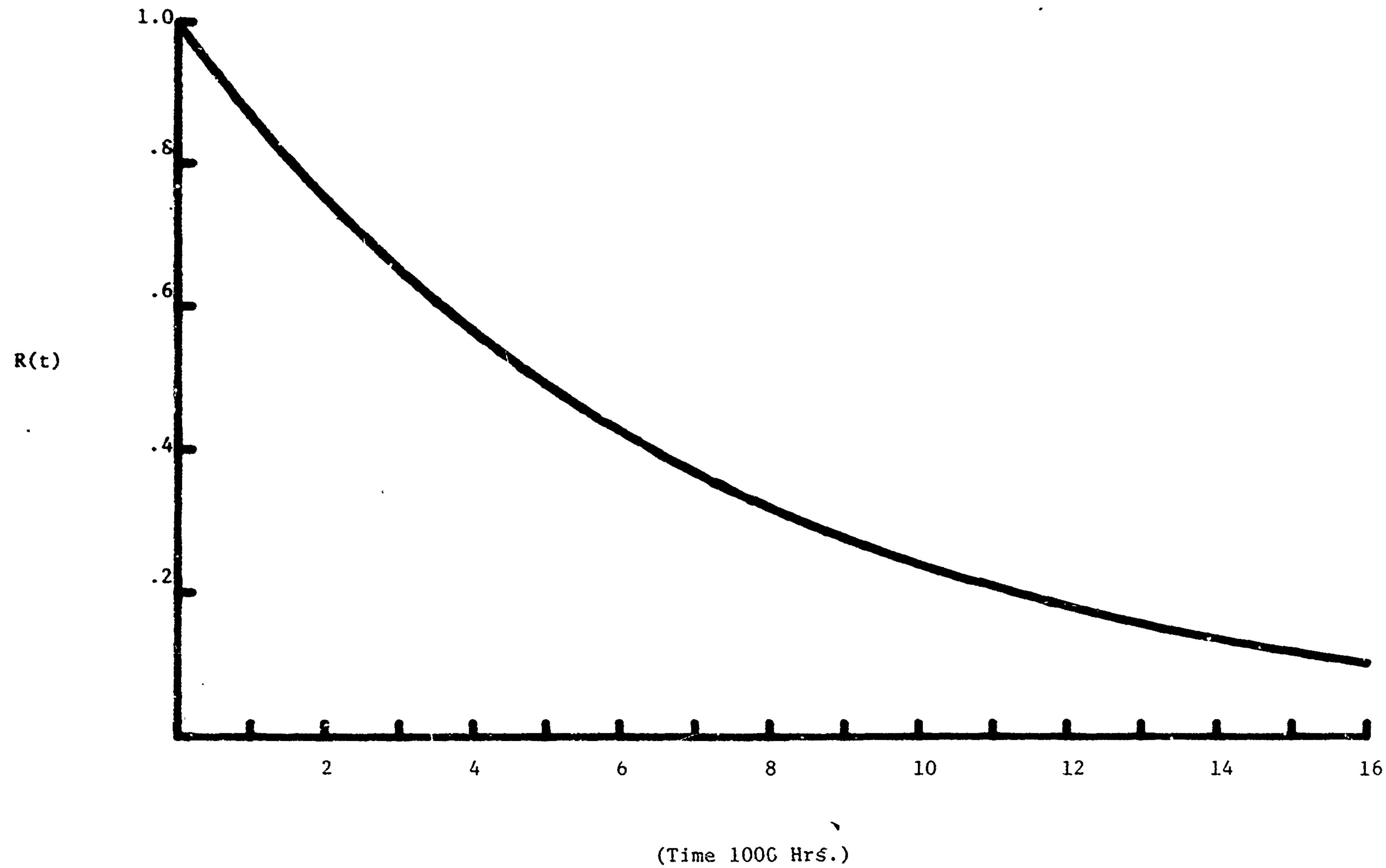


Figure A-89 6952 GRIDDED TUBE RELIABILITY R(t)

(λ = 390)

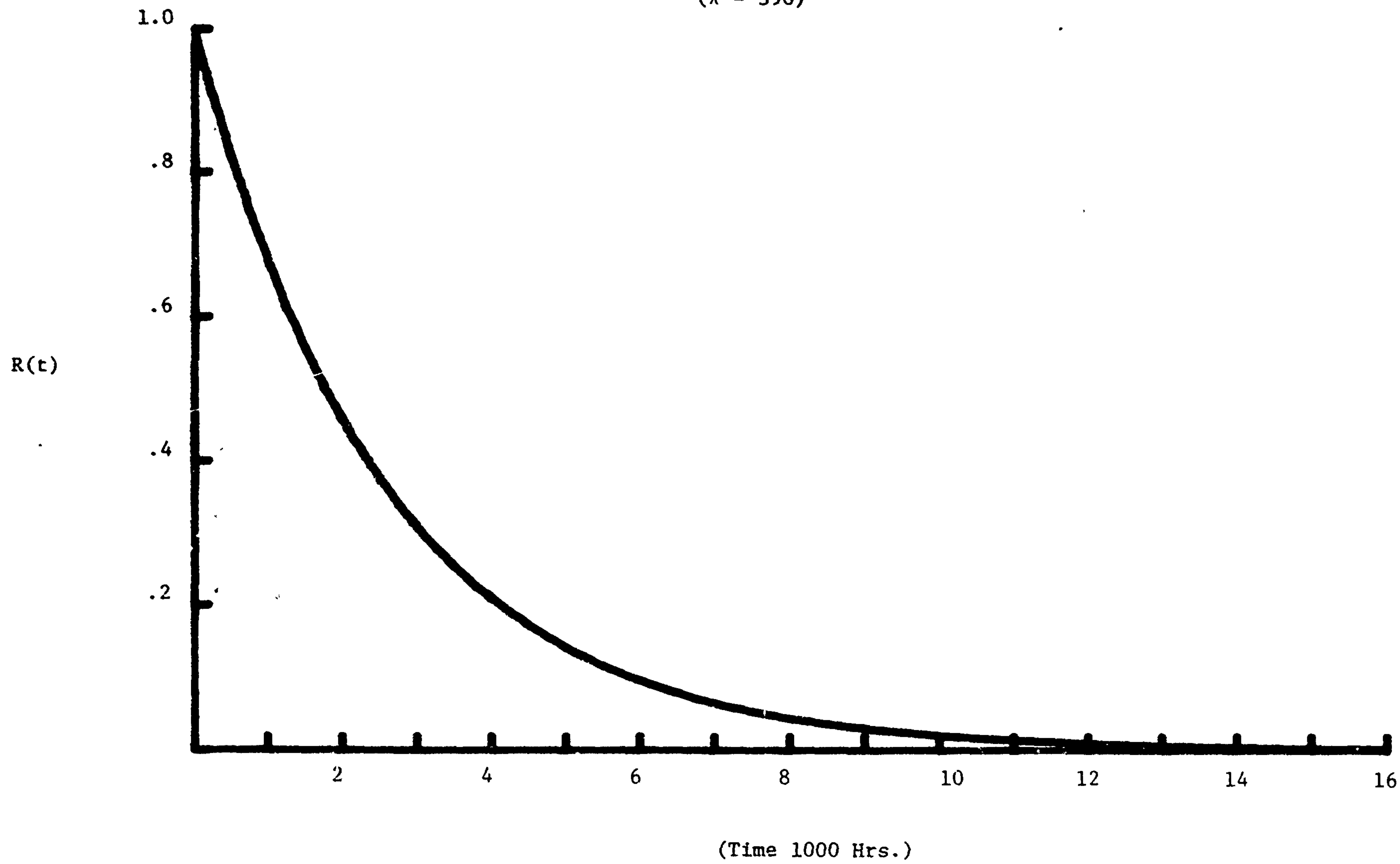


Figure A-90 QK681 AMPLITRON RELIABILITY, R(t)

(λ = 260)

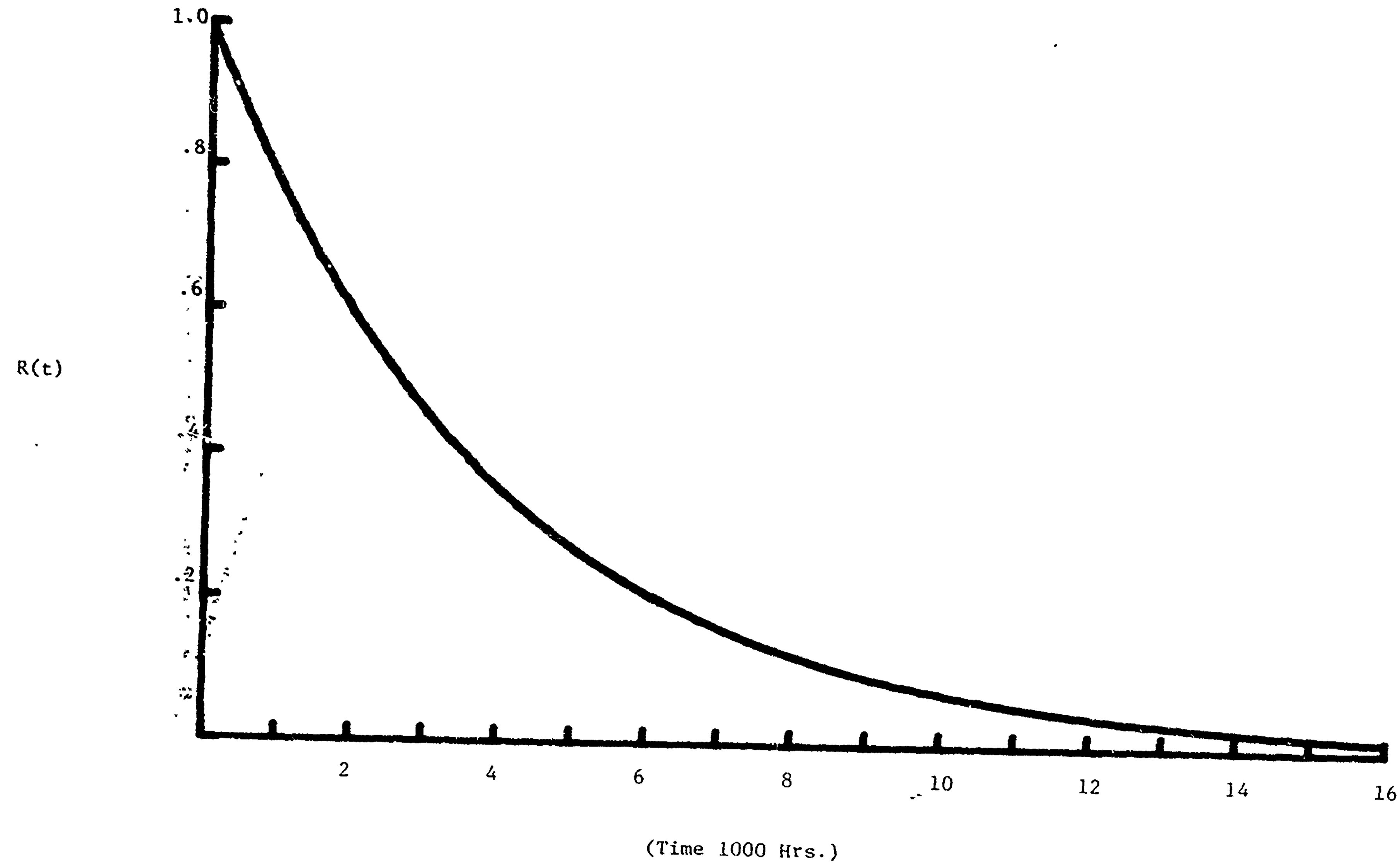


Figure A-91 SFD261 CROSSED FIELD AMPLIFIER RELIABILITY, R(t)

(λ = 209)

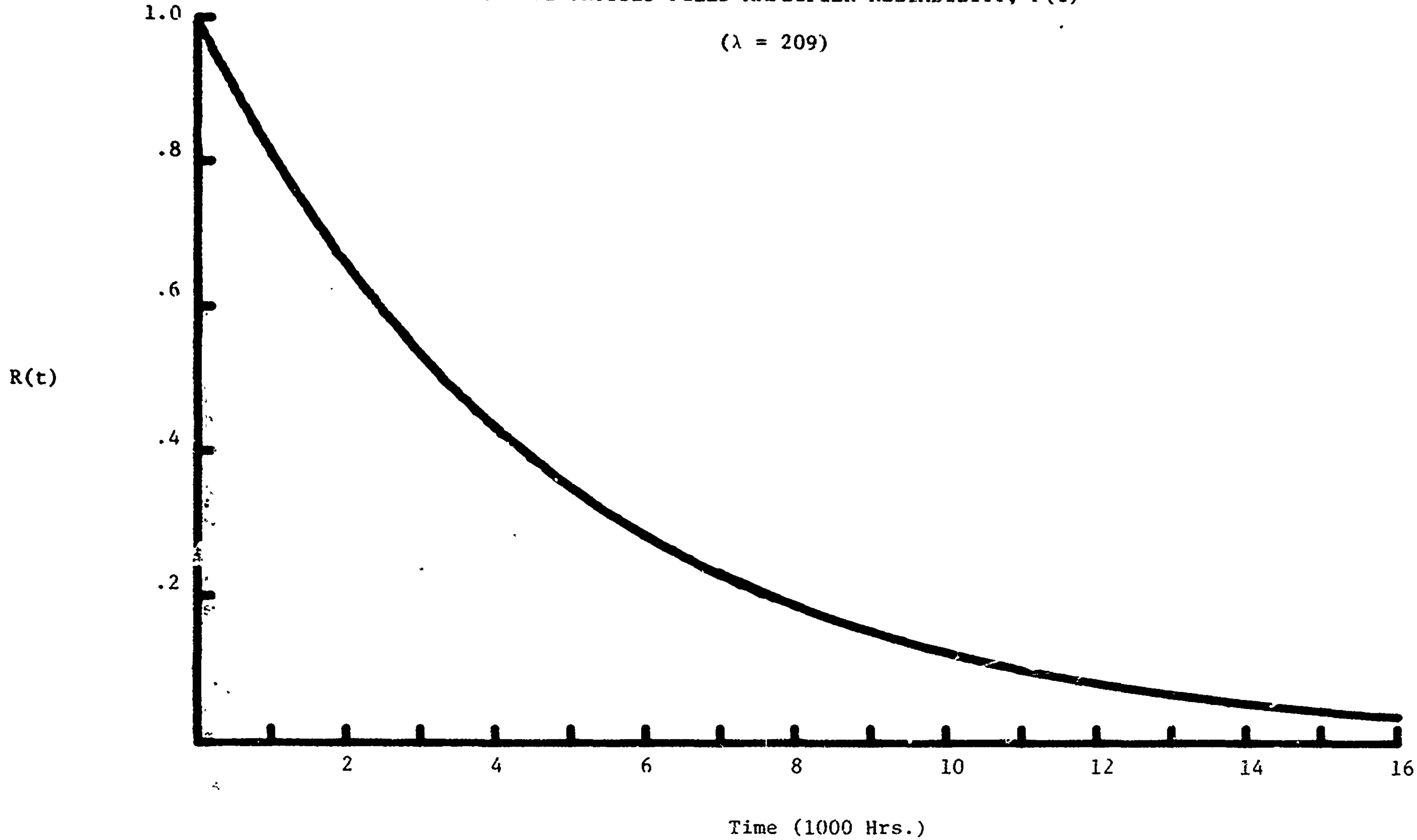


Figure A-92 SFD261 (MANUFACTURER'S DATA) CROSSED FILED AMPLIFIER RELIABILITY, R(t)

(λ = 127)