Technical Note 1975-60

C. W. Niessen

Satellite Communications Availability — Launch Scheduling

18 November 1975

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

SATELLITE COMMUNICATIONS AVAILABILITY – LAUNCH SCHEDULING

C. W. NIESSEN
Group 67

TECHNICAL NOTE 1975-60

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ABSTRACT

This report considers the scheduling of periodic launches of communications satellites in order to maintain a required level of system availability. Since satellite lifetimes can be described only statistically, availability is described by the probability of having at least "A" satellites operating in orbit as a function of time. The behavior of this probability is calculated for variations in launch rate (satellites per year), multiplicity of launch (satellites per launch vehicle), and satellite failure model. The transient in availability at the introduction of a satellite system is seen clearly in the data curves.

The data in this report can be used to choose a launch strategy which meets specified availability requirements and minimizes the number of satellites that must be procured and launched over a program lifetime.

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I. INTRODUCTION

A basic factor in the cost of MILSATCOM systems is the rate at which satellites must be procured and launched to establish and maintain a space segment capable of providing some desired level of communication service. Since the time at which any given satellite will fail cannot be predicted with certainty, one can, in fact, talk only about the probability of maintaining some desired level of service. In particular, if "A" working satellites are necessary (on appropriate orbital stations) to provide the required service, the availability of the system can be described by the probability of having at least A working satellites in orbit.

This probability is determined statistically by assuming a failure model for an individual spacecraft and a failure model for the launch process. Then, if the schedule of launch dates is known it is possible to determine the probability of A satellites working as a function of time.

This report calculates the probability of at least A satellites working in orbit as a function of time for a pre-planned periodic launch schedule. Results are calculated for two different satellite failure models and for 5 different launch rates (satellites/year). Also included is the option of launching with one, two, or four satellites per launch vehicle, so that the effect of multiple launches on system availability can be seen. The results are useful for planning purposes (i.e. estimating the average launch rate necessary to maintain a system), but are not meant to suggest that a fixed, periodic launch schedule is best; launching replenishments only on failure of orbiting spacecraft may be more desirable. Likewise, this report does not consider the effects of partial failures in a satellite or whether the working satellites are on the right orbital stations. Of particular interest is the "start-up transient" --the rise in availability with time that accompanies the introduction of a new satellite; the curves presented here indicate that this buildup is quite slow if the launch rate appropriate for steady-state maintenance is followed. This means that an initially higher launch rate may be appropriate.

II. PROBABILISTIC MODEL

There exists an entire literature on probabilistic life-time models for spacecraft. This report will use only two simple models for numerical calculations; however, the formulas generated can be used with any model desired.

The first life mode used is the so-called exponential life model, in which the probability that a satellite is still working at time t after a successful launch is

$$P(t) = e^{-t/\tau} \quad ; t \geq 0$$

This model assumes that the probability density function of the time of failure is

$$p(t) = \frac{1}{\tau} e^{-t/\tau} \quad ; t \geq 0$$

(Thus given that it lasts until t, failure between t and t + dt is just dt/τ , a constant.)

The second life model used is the so-called linear life model in which

$$P(t) = \begin{cases} 1 - \frac{t}{2\tau} & ; 0 \leq t \leq 2\tau \\ 0 & ; \text{otherwise} \end{cases}$$

This model assumes that the time of failure is equally likely over a fixed period; that is, the probability density function of the time of failure is

$$p(t) = \frac{1}{2\tau} \quad ; 0 < t < 2\tau$$

In both cases the mean (average) lifetime is τ since

$$\int_0^\infty P(t)dt = \int_0^\infty tp(t)\,dt = \tau$$

We also assume a particularly simple model for the success of launch: a launch is either successful with probability s or unsuccessful with probability 1-s. We do not consider partial successes, such as if one of several satellites on the launch vehicle fails to separate.

III. AVERAGE BEHAVIOR

The average number of satellites that will be working given a long history of periodic launches is not a function of the life model nor of the launch strategy (number of satellites per launch vehicle). To see that this is so, assume launches with m satellites per booster have been made every T years at times -nT ($n = 0, 1, 2, \ldots \infty$); next calculate the expected (average) number of satellites working at time t ($o \leq t < T$), and then average over t. For one launch at time -nT, the expected number of satellites surviving to time t is clearly

$$msP(nT + t)$$

so that for all launches the average number of working satellites is

$$ms \sum_{n=o}^{\infty} P(nT + t) .$$

Now averaging this number over t ($o \leq t < T$), we obtain

$$\eta = \frac{1}{T} \int_{o}^{T} ms \sum_{n=o}^{\infty} P(nT + t)\, dt$$

$$= \frac{ms}{T} \sum_{n=o}^{\infty} \int_{nT}^{(n+1)T} P(t)\, dt$$

$$= \frac{ms}{T} \int_{o}^{\infty} P(t)\, dt$$

$$= \frac{ms\tau}{T}$$

as the average number of satellites operating, which is independent of the form of the life model but depends only on the rate of launch (m/T), the launch success probability (s) and the mean lifetime of the satellite (τ).

IV. PROBABILISTIC BEHAVIOR

The analysis of Sec. III does not say anything about the variation about the mean that would result from the fact that satellite lifetimes are random variables. In this section we calculate the probability of exactly y satellites surviving at time nT (n = 1, 2, ...) from the beginning of a launch series with first launch at t = 0 and subsequent launches of m satellites every T years. (The calculation at time nT is made just before the next launch.) From this calculation, we then obtain the probability of at least A satellites working at time nT which is what is needed to specify system availability.

Let x(n) be a random variable which is the number of satellites surviving a launch of m satellites after nT years. Then

$$x(n) = \begin{cases} 0 \text{ with probability } P_0(n) \\ 1 \text{ with probability } P_1(n) \\ 2 \text{ with probability } P_2(n) \\ \vdots \\ m \text{ with probability } P_m(n) \end{cases}$$

The values of the $P_i(n)$'s must, of course, sum to 1 and are determined by the life model and launch success probability, s, as

$$P_i(n) = \begin{cases} s \binom{m}{i} P^i(nT) \left[1 - P(nT)\right]^{m-i} & i = 1, 2, \ldots m \\ (1 - s) + s \left[1 - P(nT)\right]^m & i = 0 \end{cases}$$

where P(t) is taken to be the appropriate life model from Sec. II.

After N periods of time from the start of the launch series, the total number of satellites surviving is a random variable

$$y(N) = \sum_{n=1}^{N} x(n) .$$

Now since y is the sum of statistically independent random variables, its probability density function (p.d.f.) is the convolution of the probability density functions of the x(n)'s. This operation can most easily be carried out using a z transform to obtain

$$\text{p.d.f. of } x(n) \Rightarrow \sum_{i=o}^{m} P_i(n) z^i$$

and the corresponding

$$\text{p.d.f. of } y(N) \Rightarrow \prod_{n=1}^{N} \left[\sum_{i=o}^{m} P_i(n) z^i \right]$$

If this product of polynomials in z is actually carried out, the coefficient of z^a is the probability of exactly "a" survivors; Pr (a at NT), and the probability of at least A survivors is then

$$\Pr(\geq A \text{ at } NT) = 1 - \sum_{a=o}^{A-1} \Pr(a \text{ at } NT).$$

This calculation has been made just before the launch at time NT. We are now interested in calculations immediately after this launch (at time "nT+"). It is easy to see that

$$\begin{aligned} \Pr(a \text{ at } NT+) = {} & (1-s) \Pr(a \text{ at } NT) \\ & + s \Pr(a-m \text{ at } NT) \end{aligned}$$

where the two terms are obviously due to the success or failure of the launch at NT.

Likewise, it is easy to show that

$$\Pr(\geq A \text{ at } NT+) = 1 - \sum_{a=o}^{A-1} \Pr(a \text{ at } NT+)$$

$$= \Pr(\geq A \text{ at } NT)$$

$$+ s \sum_{j=1}^{m} \Pr(A-j \text{ at } NT)$$

For time $nT < t < (n + 1)\ T$ we could also calculate $\Pr(\geq A)$, but for simplicity and with little practical difference for parameters of interest we will extrapolate linearly between $\Pr(\geq A \text{ at } nT+)$ and $\Pr(\geq A \text{ at } (n + 1)\ T)$. This extrapolation will be most accurate for T/γ small.

V. NUMERICAL RESULTS

The formulas of Sec. IV were evaluated on a digital computer, and the values of Pr ($\geq$ A) are shown as a function of time in the following curves. Each graph shows Pr ($\geq$A) surviving satellites for several values of A. The parameters held constant on each graph are

$\eta = \frac{ms\tau}{T}$	the average number of satellites surviving
m	the multiplicity of the launch (number of satellites per launch)
s = .85	the success probability of a launch

Note that there are two scales at the bottom. The upper scale is N, the total number of satellites that have been launched just before the scheduled launch at time NT. (Note that to prevent curves from overwriting each other, they have been successively shifted slightly to the right, so that launch times may appear not to be on integers. This is for readability only.) The lower scale is time in years, and applies for τ = 5.3 years. The curves may be corrected, however, for different τ simply by scaling this time axis proportional to τ/5.3; the shape of the curves does not change.

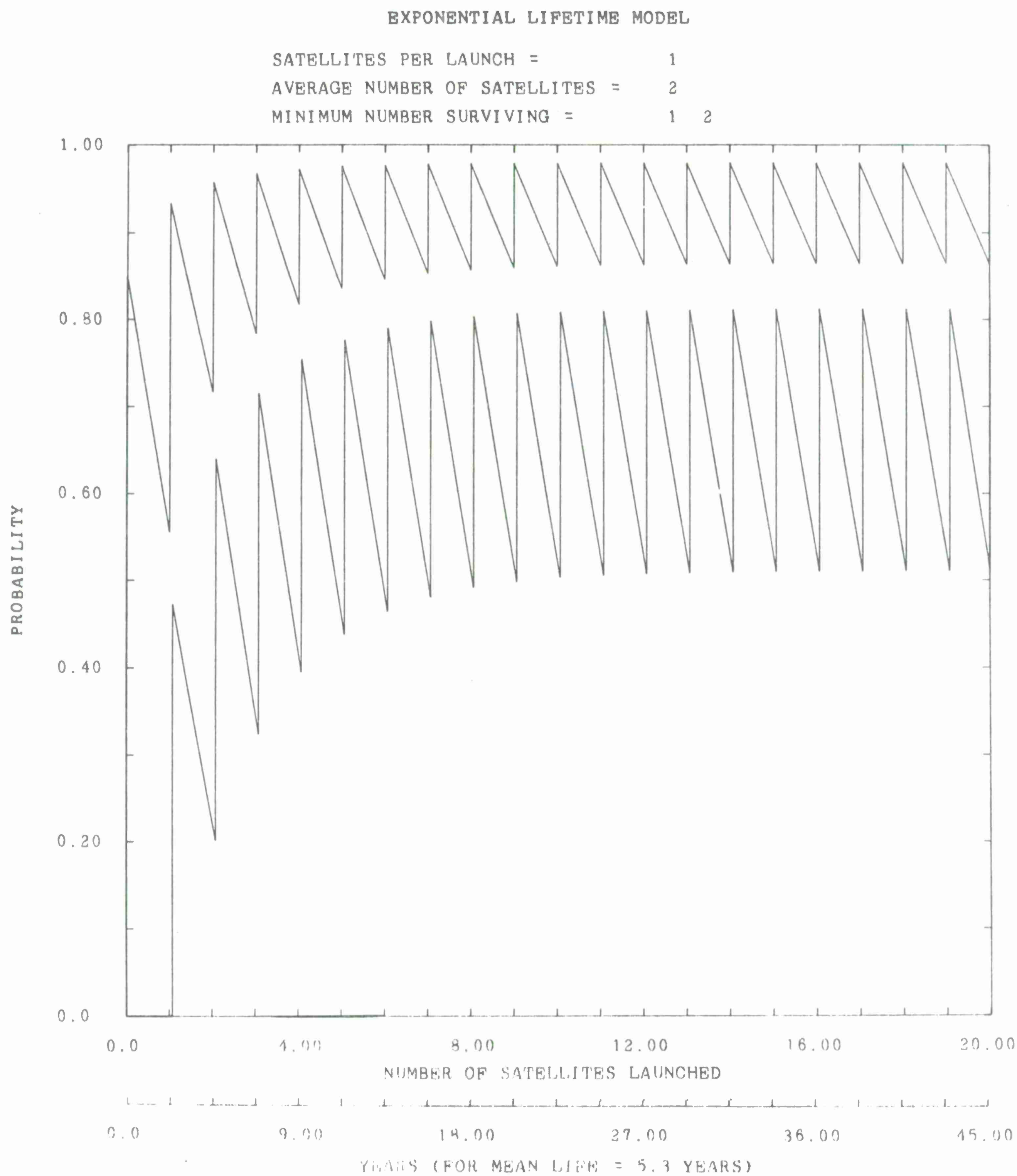
The following curves alternate between the exponential life model and the linear life model. The values taken on by other parameters are

$$m = 1, 2, 4$$

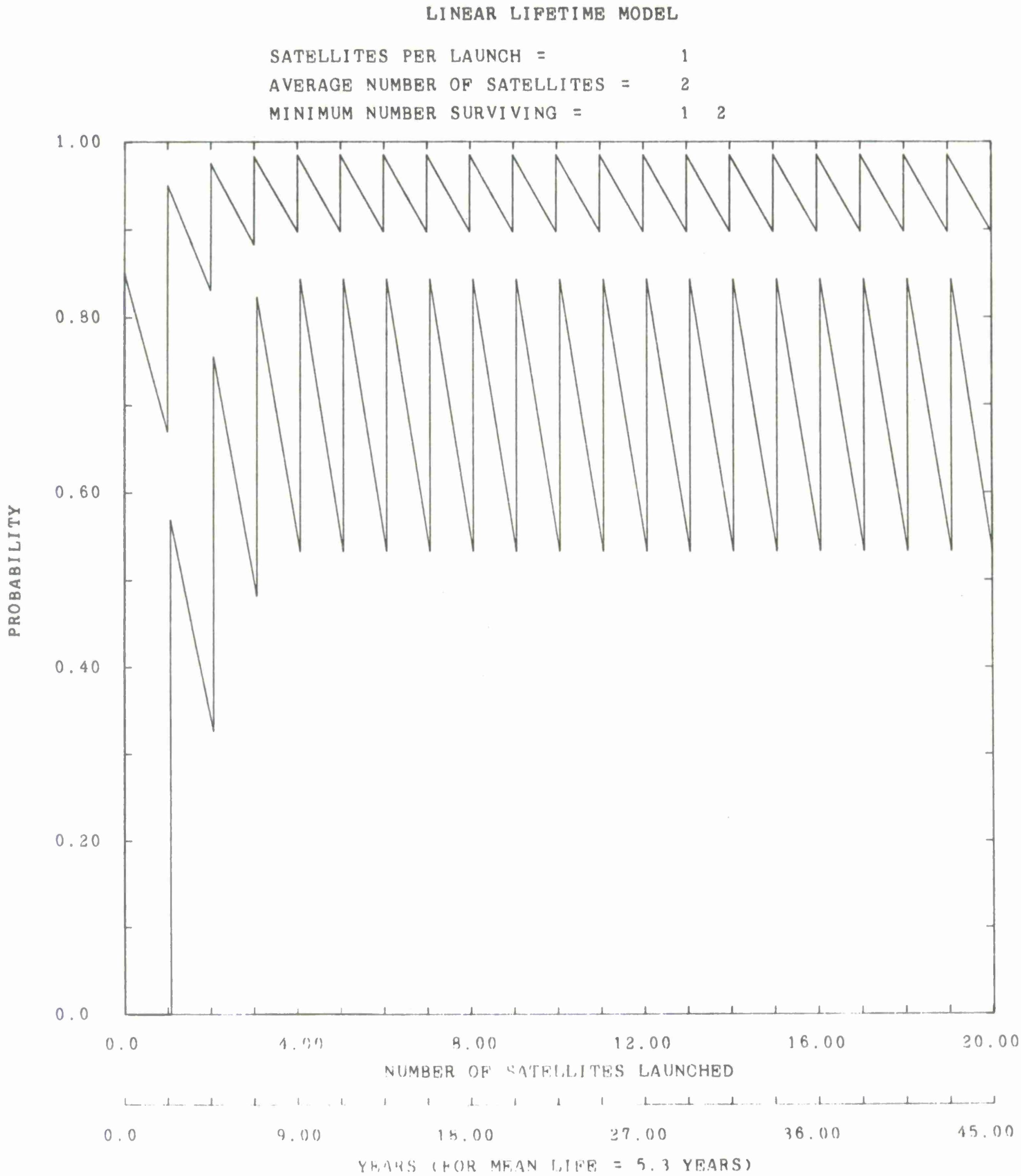
$$\eta = 2, 4, 6, 9, 12$$

and T takes on values appropriate to η.

Interpretation of these curves follows in Sec. VI.



EXPONENTIAL LIFETIME MODEL
SATELLITES PER LAUNCH = 1
AVERAGE NUMBER OF SATELLITES = 2
MINIMUM NUMBER SURVIVING = 1 2
1.00
0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
18.00
27.00
36.00
(FOR MEAN LIFE = 5.3 YEARS)


LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 1
AVERAGE NUMBER OF SATELLITES = 2
MINIMUM NUMBER SURVIVING = 1 2
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
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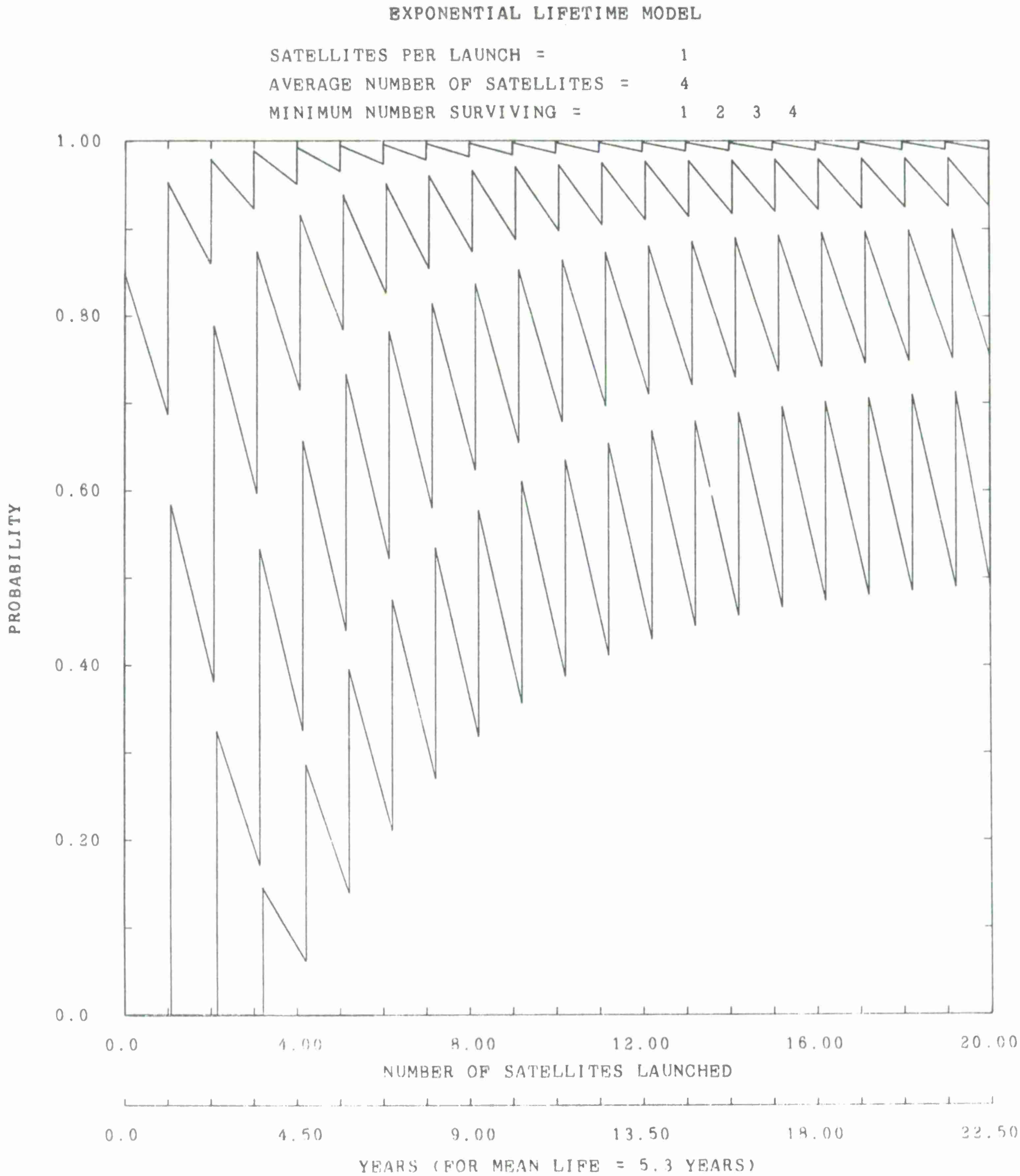
9.00
18.00
27.00
36.00
45.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)


EXPONENTIAL LIFETIME MODEL
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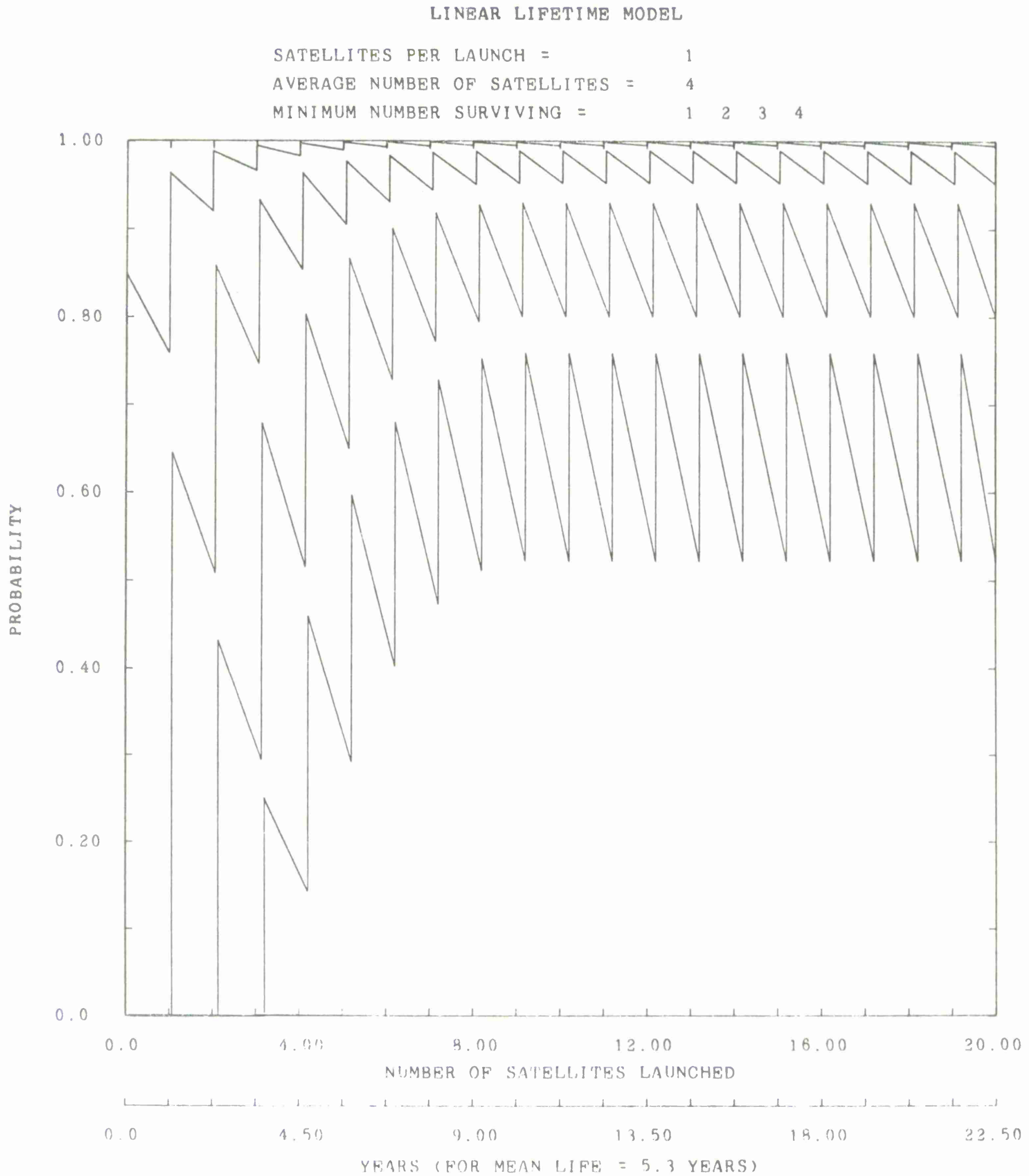
AVERAGE NUMBER OF SATELLITES = 4
MINIMUM NUMBER SURVIVING = 1 2 3 4
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
4.50
9.00
13.50
18.00
22.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)


LINEAR LIFETIME MODEL
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AVERAGE NUMBER OF SATELLITES = 4
MINIMUM NUMBER SURVIVING = 1 2 3 4
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
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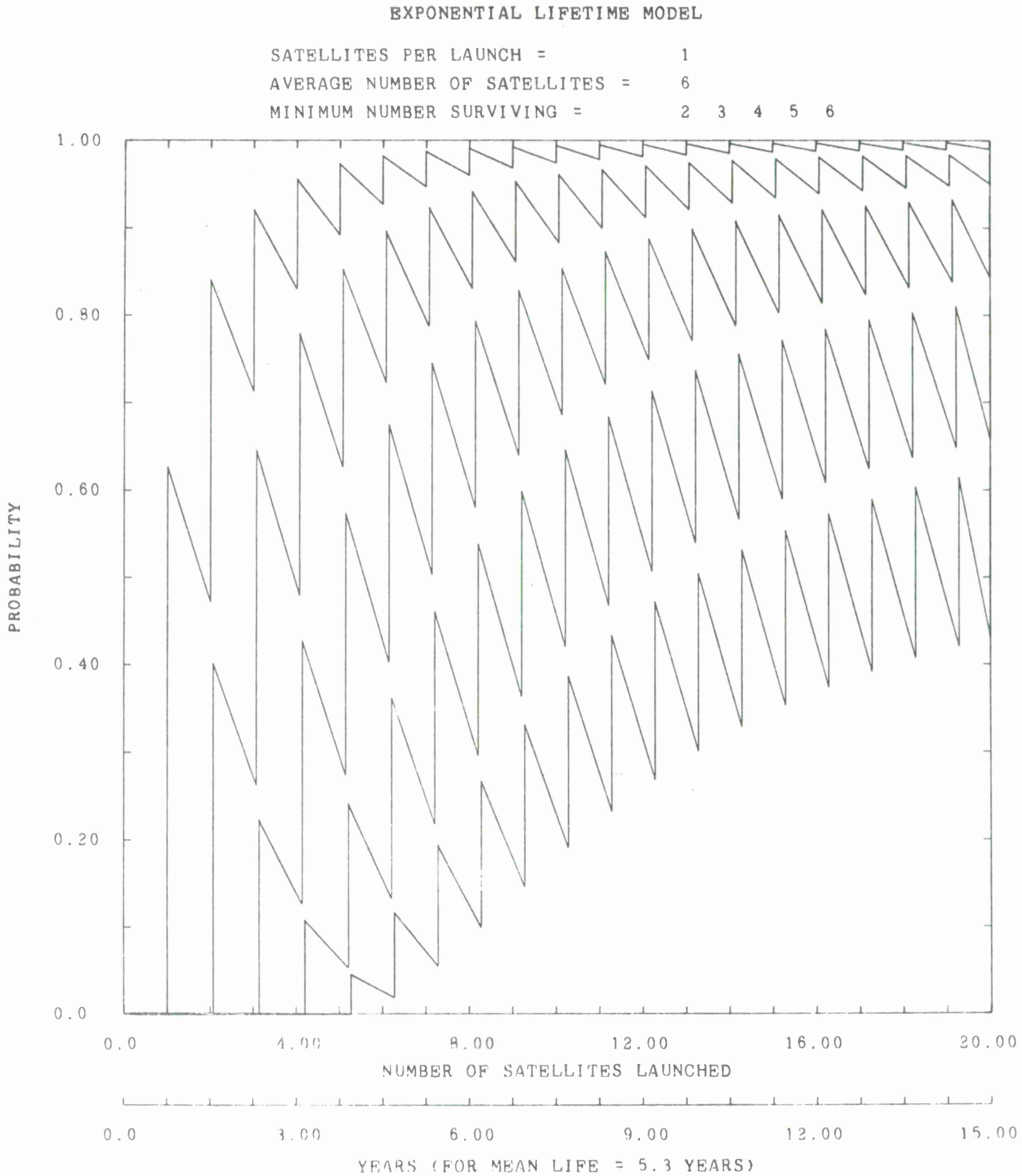
4.50
9.00
13.50
18.00
22.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)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MINIMUM NUMBER SURVIVING = 2 3 4 5 6
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0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
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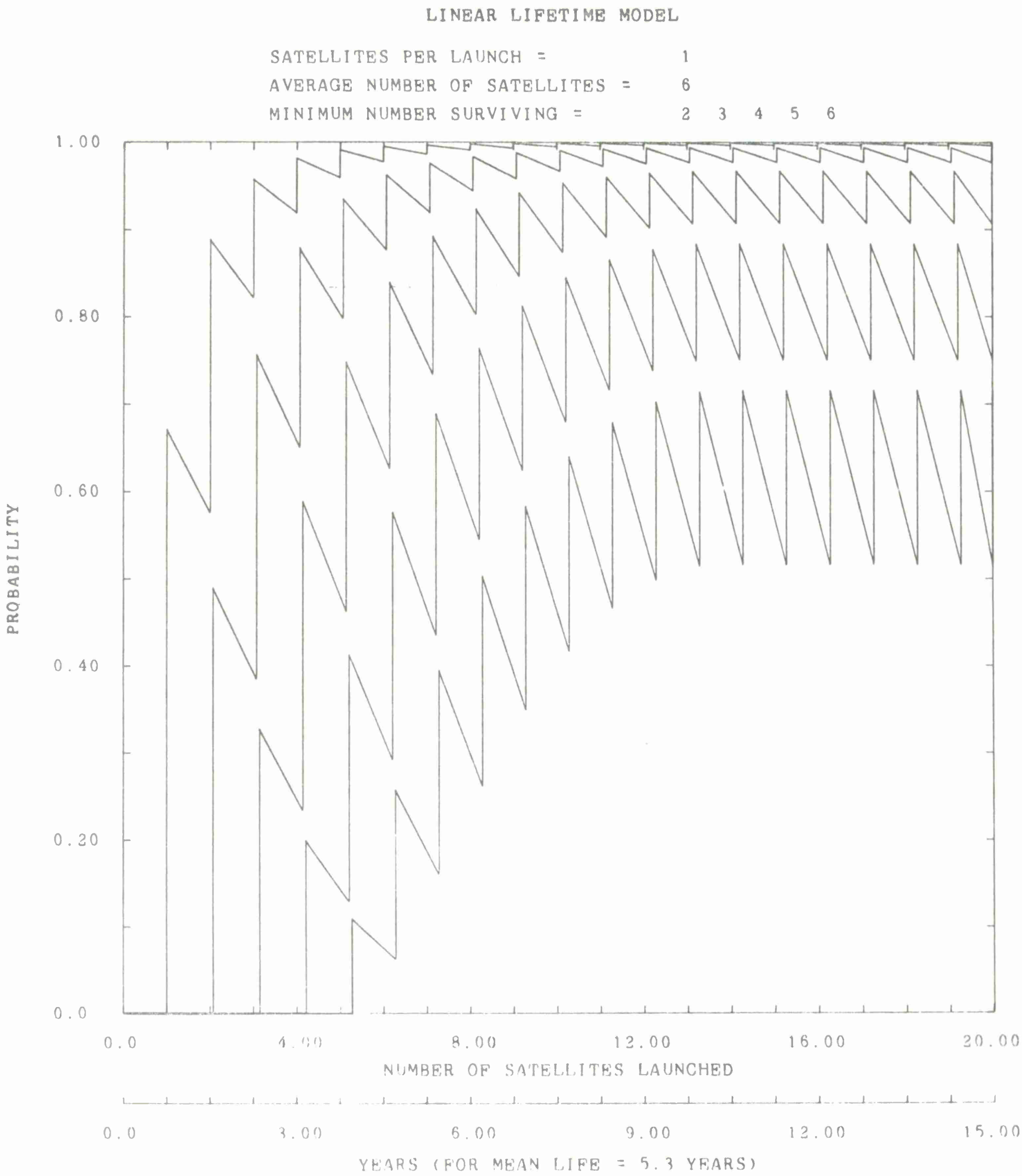
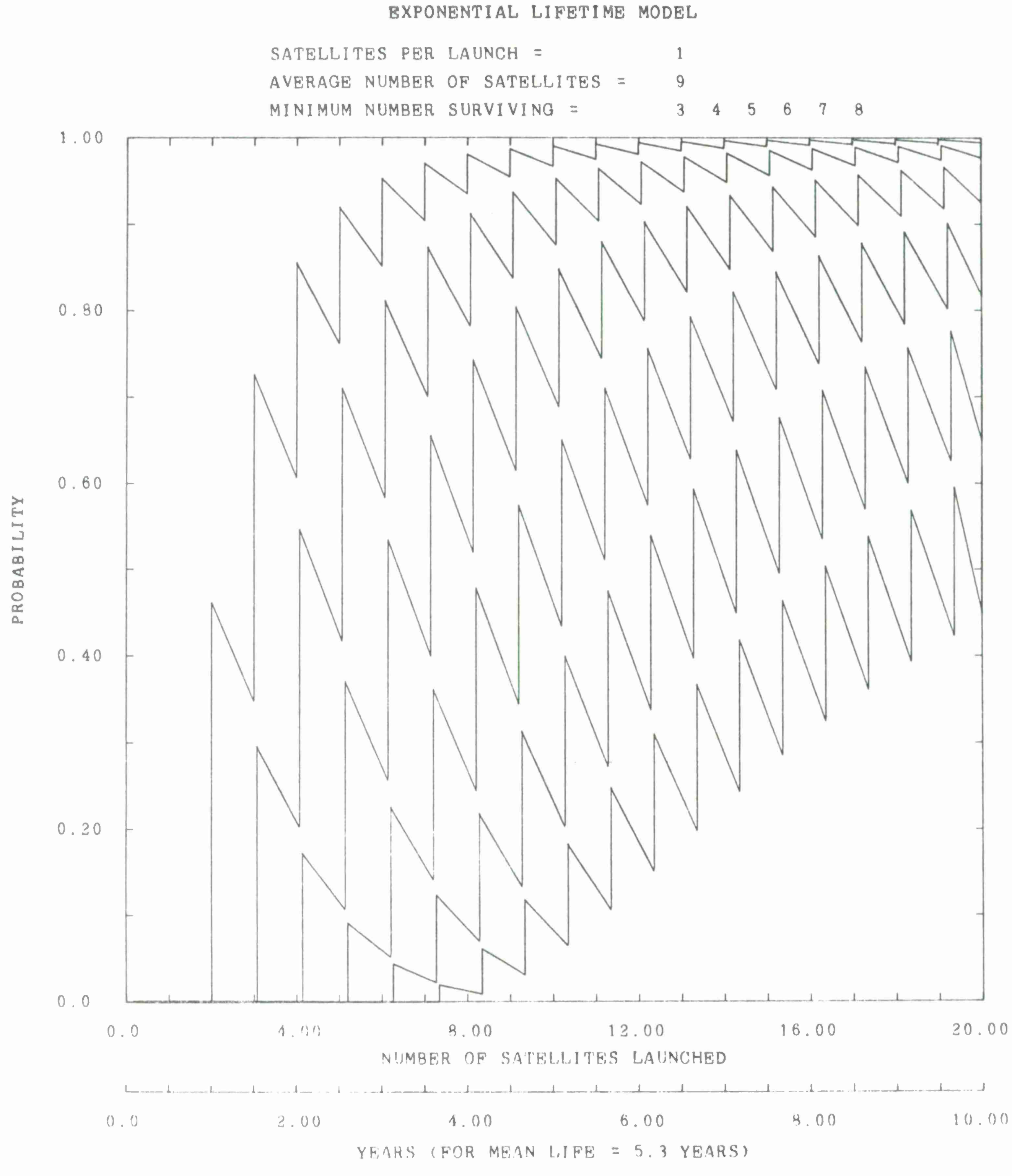
9.00
12.00
15.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)



LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 1
AVERAGE NUMBER OF SATELLITES = 6
MINIMUM NUMBER SURVIVING = 2 3 4 5 6
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
3.00
6.00
9.00
12.00
15.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)


EXPONENTIAL LIFETIME MODEL
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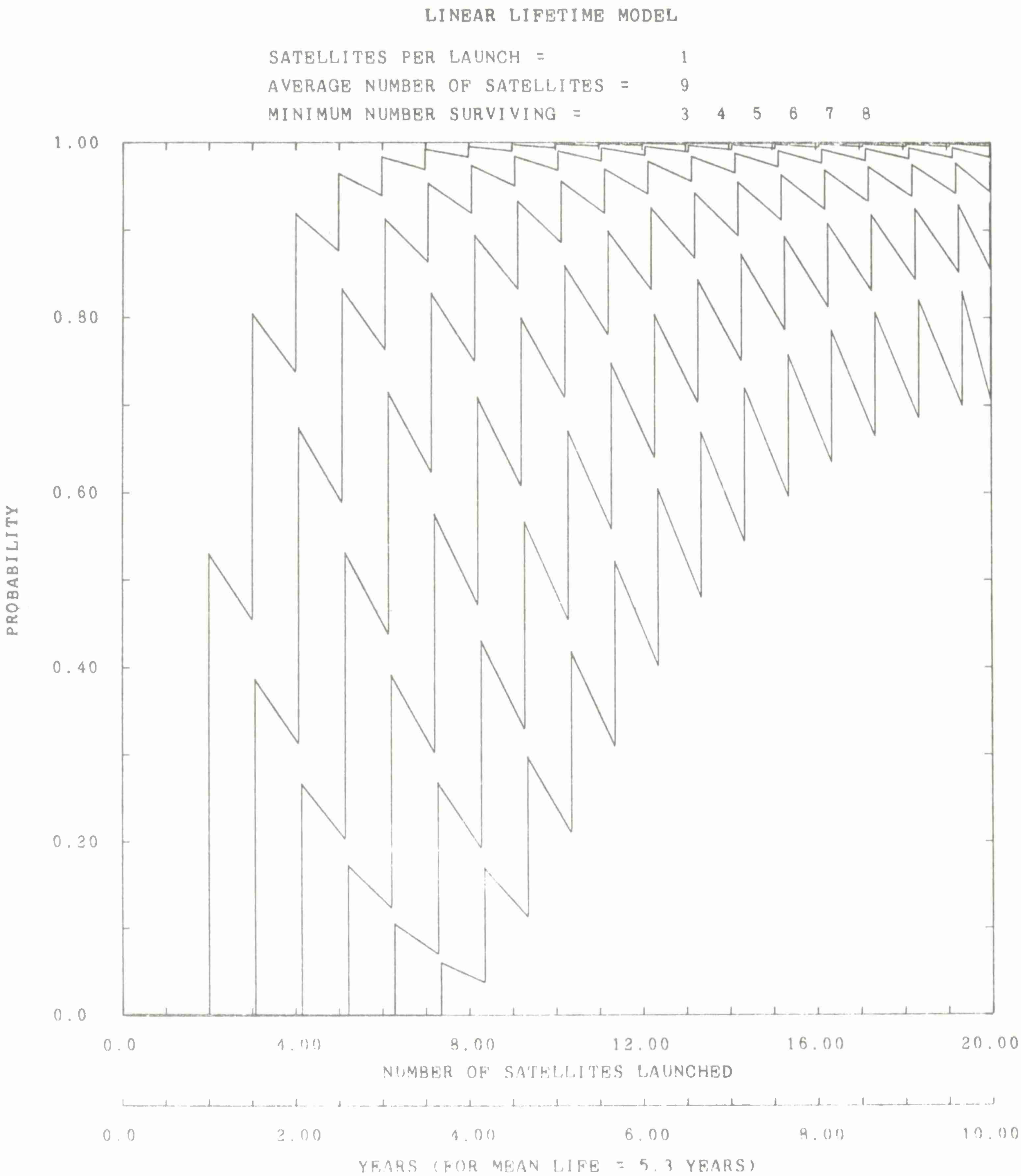
AVERAGE NUMBER OF SATELLITES = 9
MINIMUM NUMBER SURVIVING = 3 4 5 6 7 8
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
2.00
4.00
6.00
8.00
10.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)


LINEAR LIFETIME MODEL
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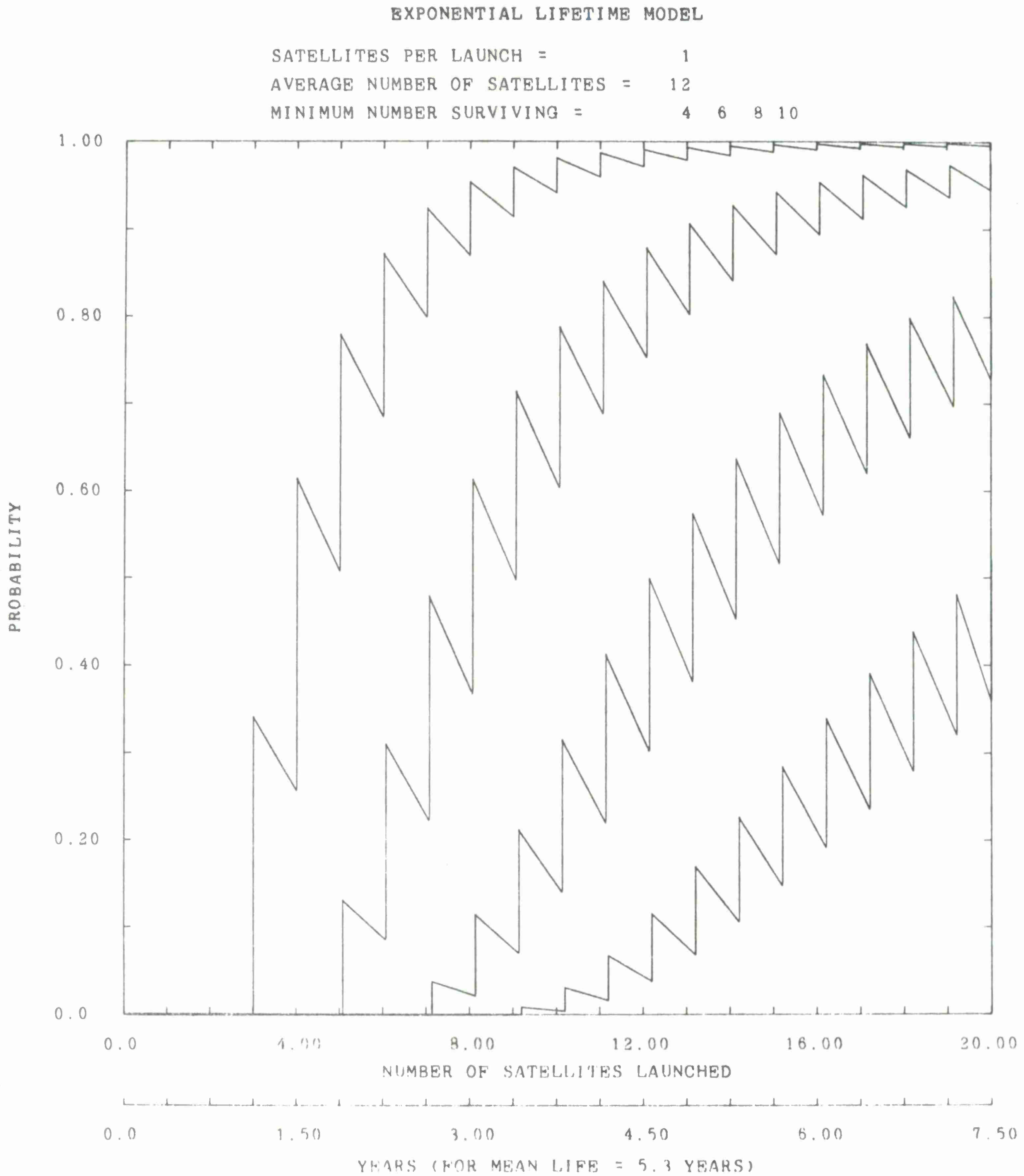
AVERAGE NUMBER OF SATELLITES = 9
MINIMUM NUMBER SURVIVING = 3 4 5 6 7 8
1.00
0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
2.00
4.00
6.00
8.00
10.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)


EXPONENTIAL LIFETIME MODEL
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AVERAGE NUMBER OF SATELLITES = 12
MINIMUM NUMBER SURVIVING = 4 6 8 10
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0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
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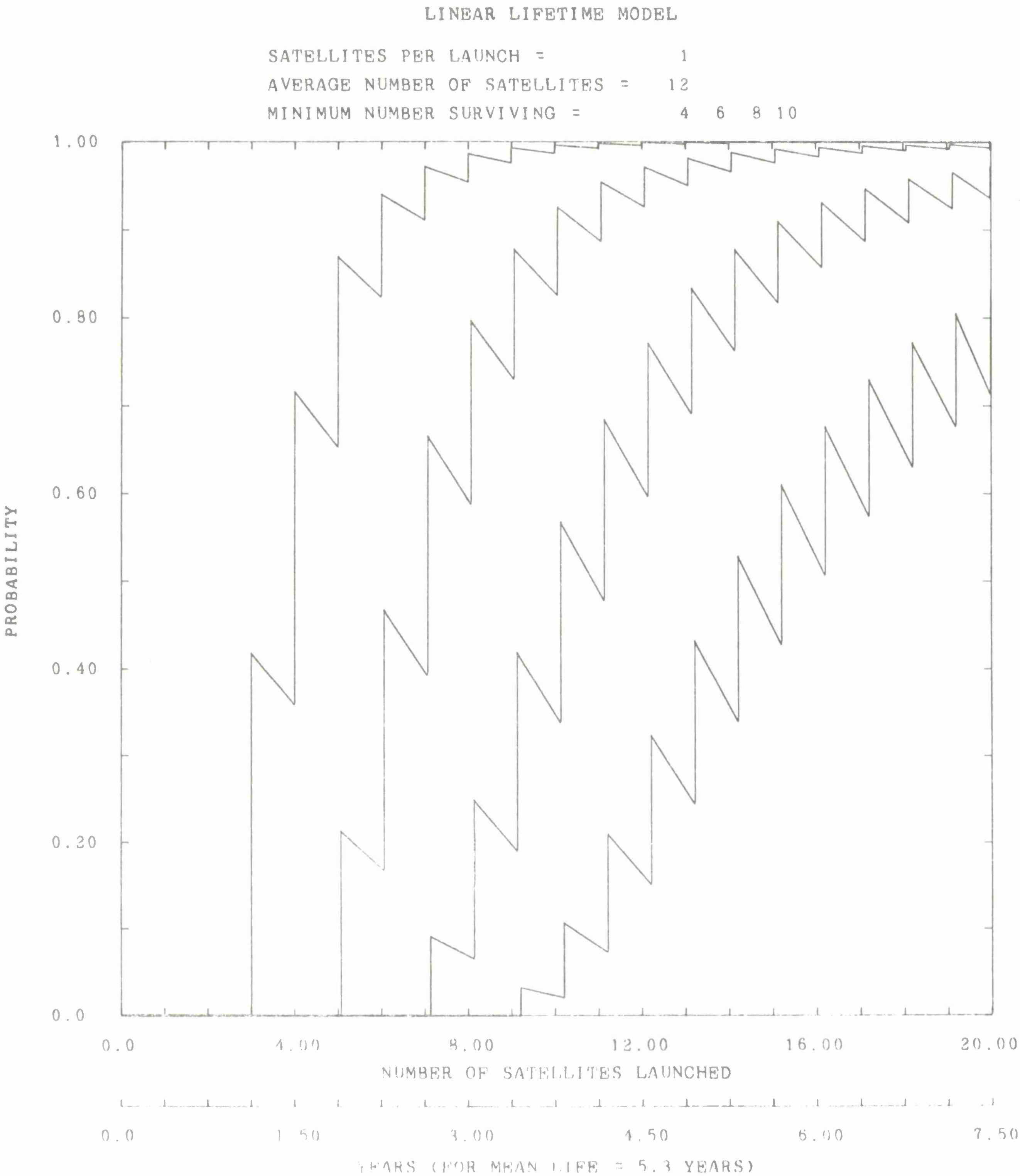
1.50
3.00
4.50
6.00
7.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)


LINEAR LIFETIME MODEL
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AVERAGE NUMBER OF SATELLITES = 12
MINIMUM NUMBER SURVIVING = 4 6 8 10
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
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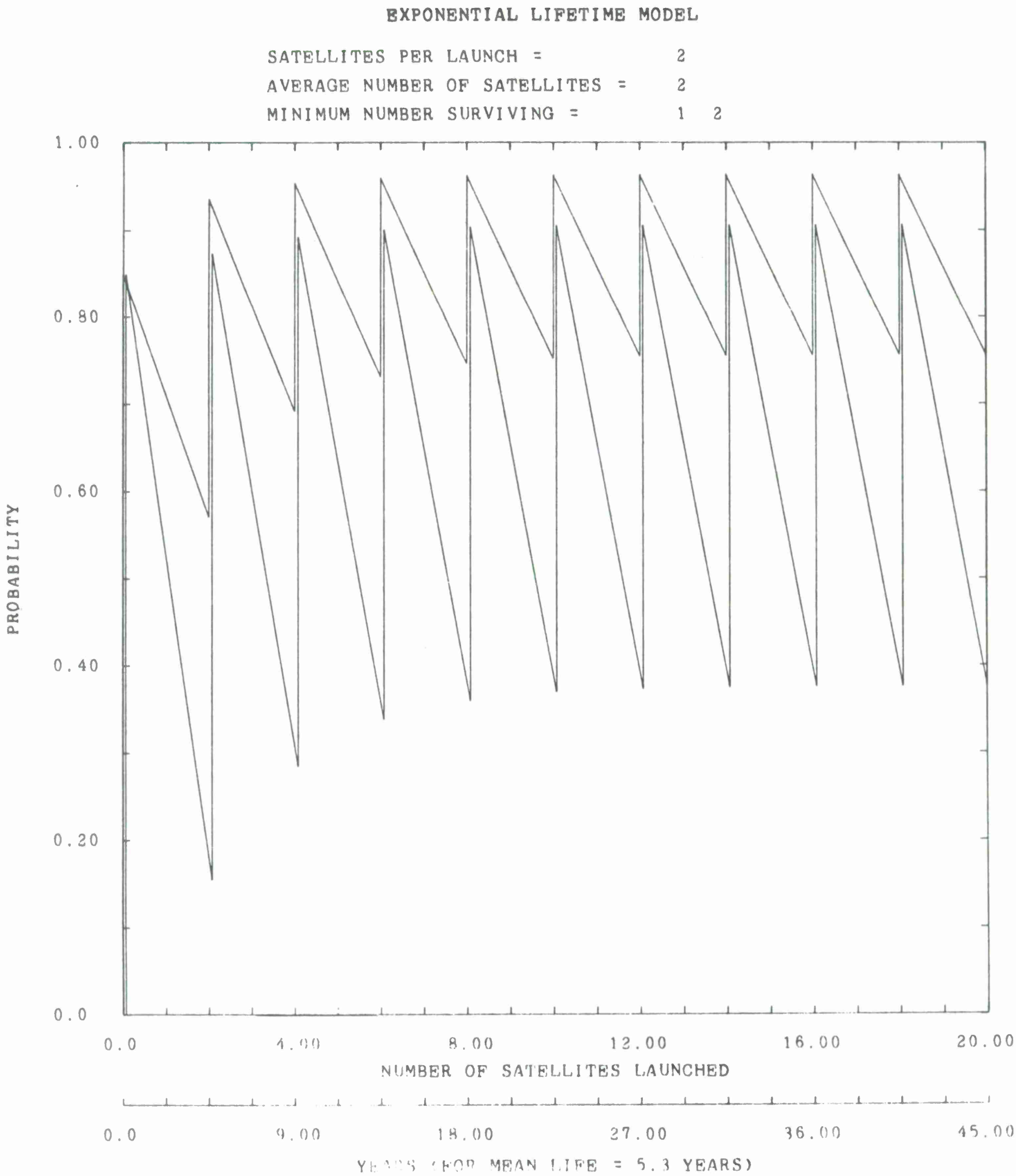
1.50
3.00
4.50
6.00
7.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)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MINIMUM NUMBER SURVIVING = 1 2
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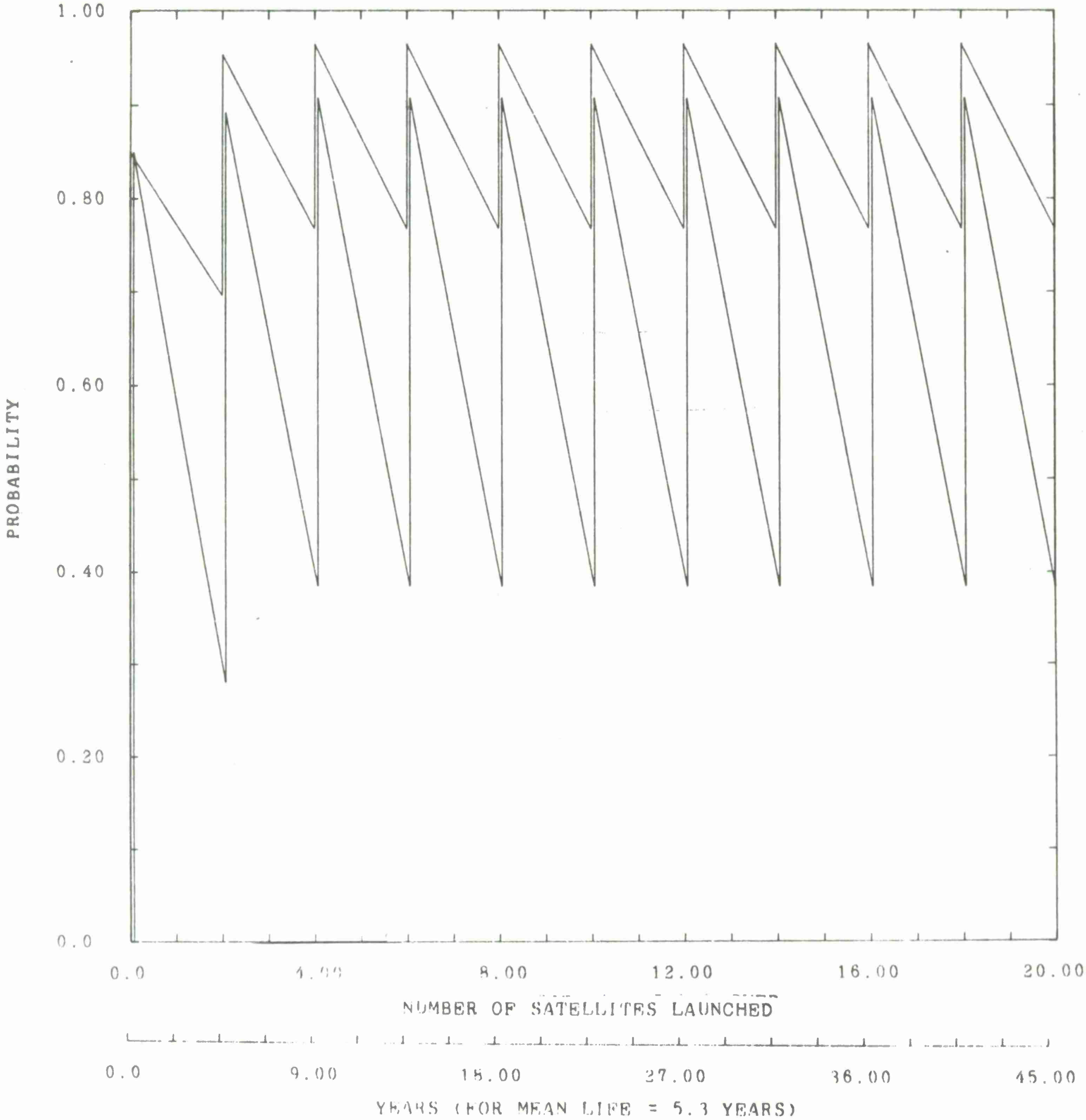
0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
18.00
27.00
45.00
MEAN LIFE = 5.3 YEARS)

LINEAR LIFETIME MODEL

SATELLITES PER LAUNCH = 2

AVERAGE NUMBER OF SATELLITES = 2

MINIMUM NUMBER SURVIVING = 1 2

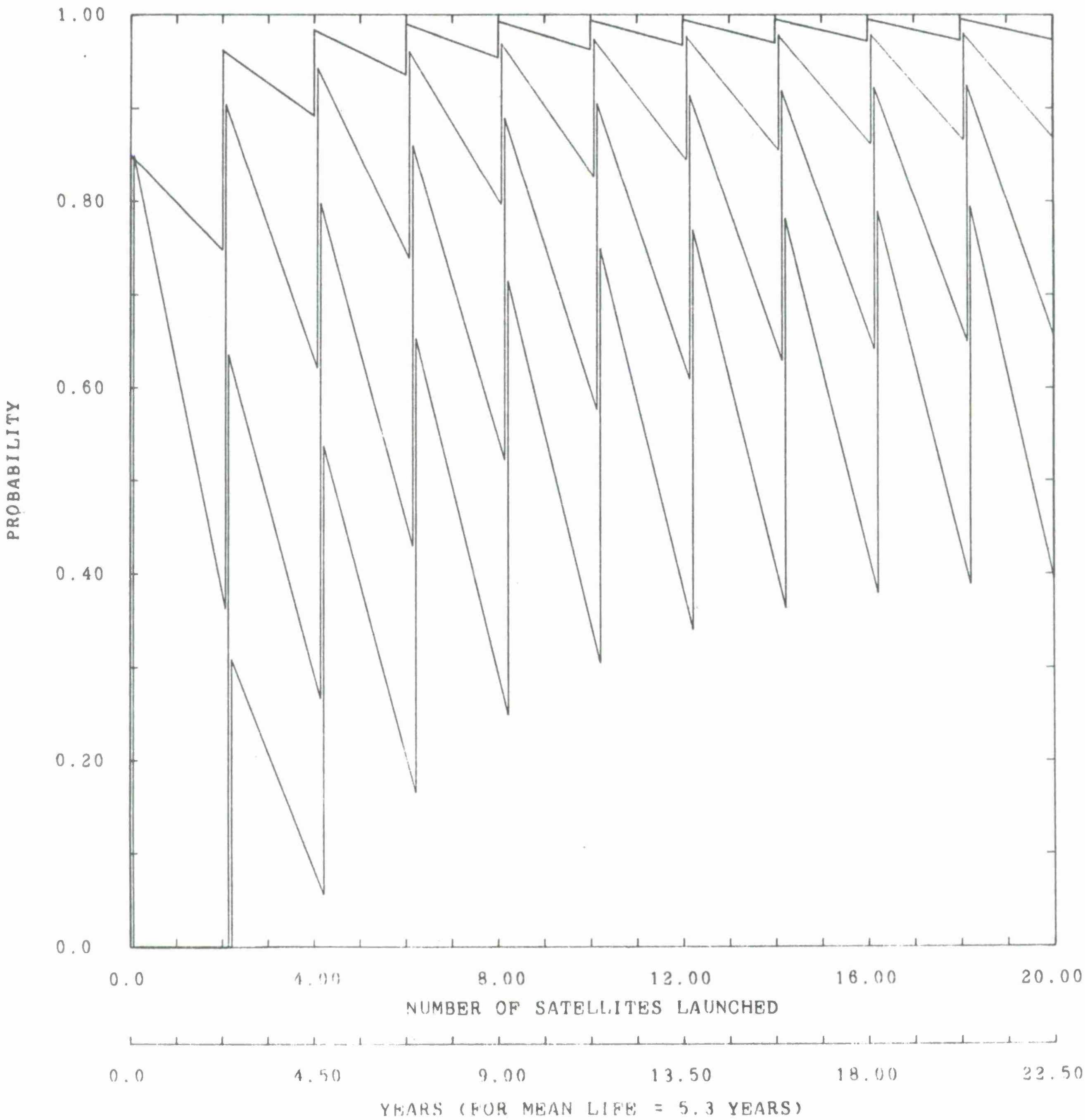


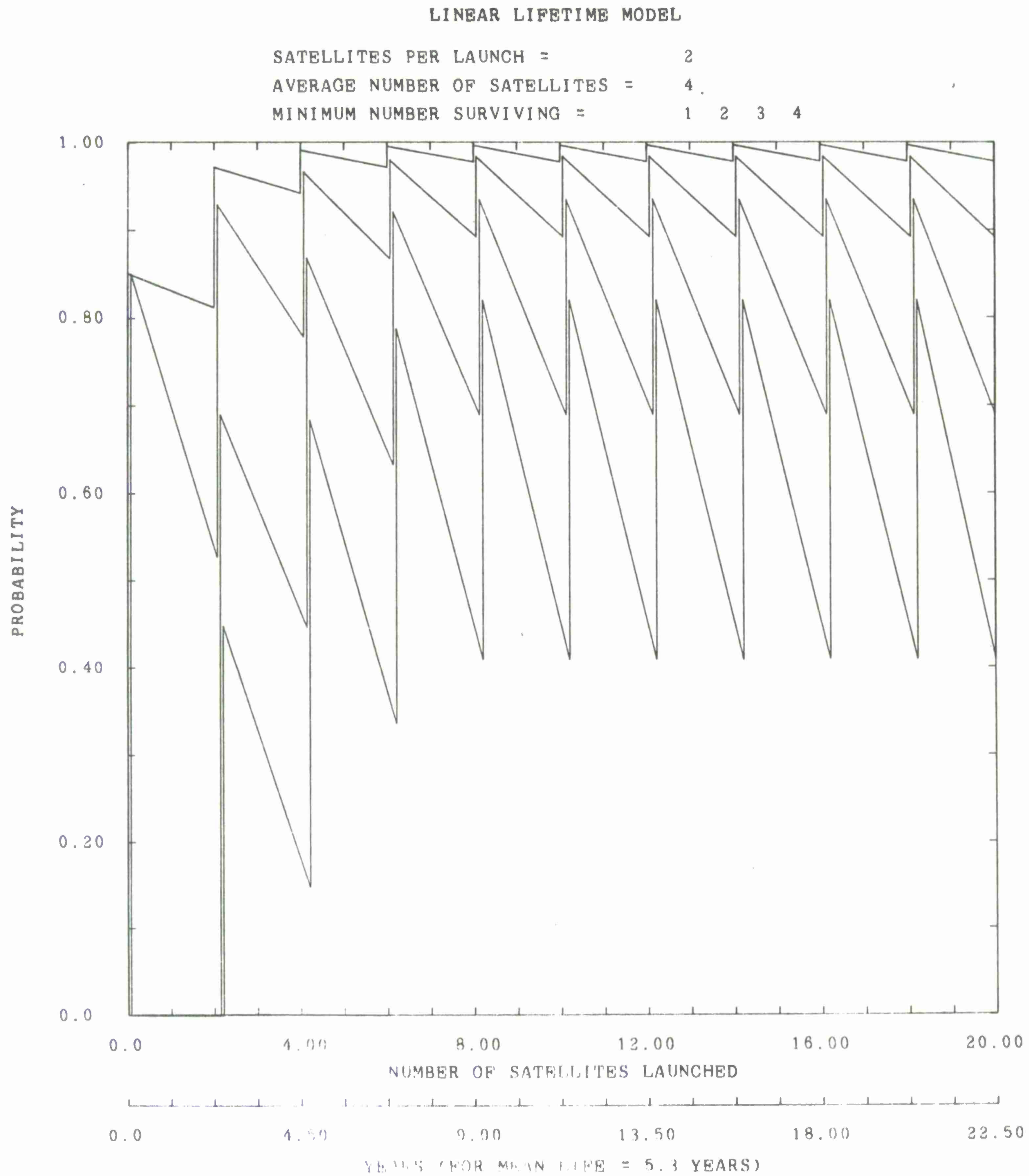
EXPONENTIAL LIFETIME MODEL

SATELLITES PER LAUNCH = 2

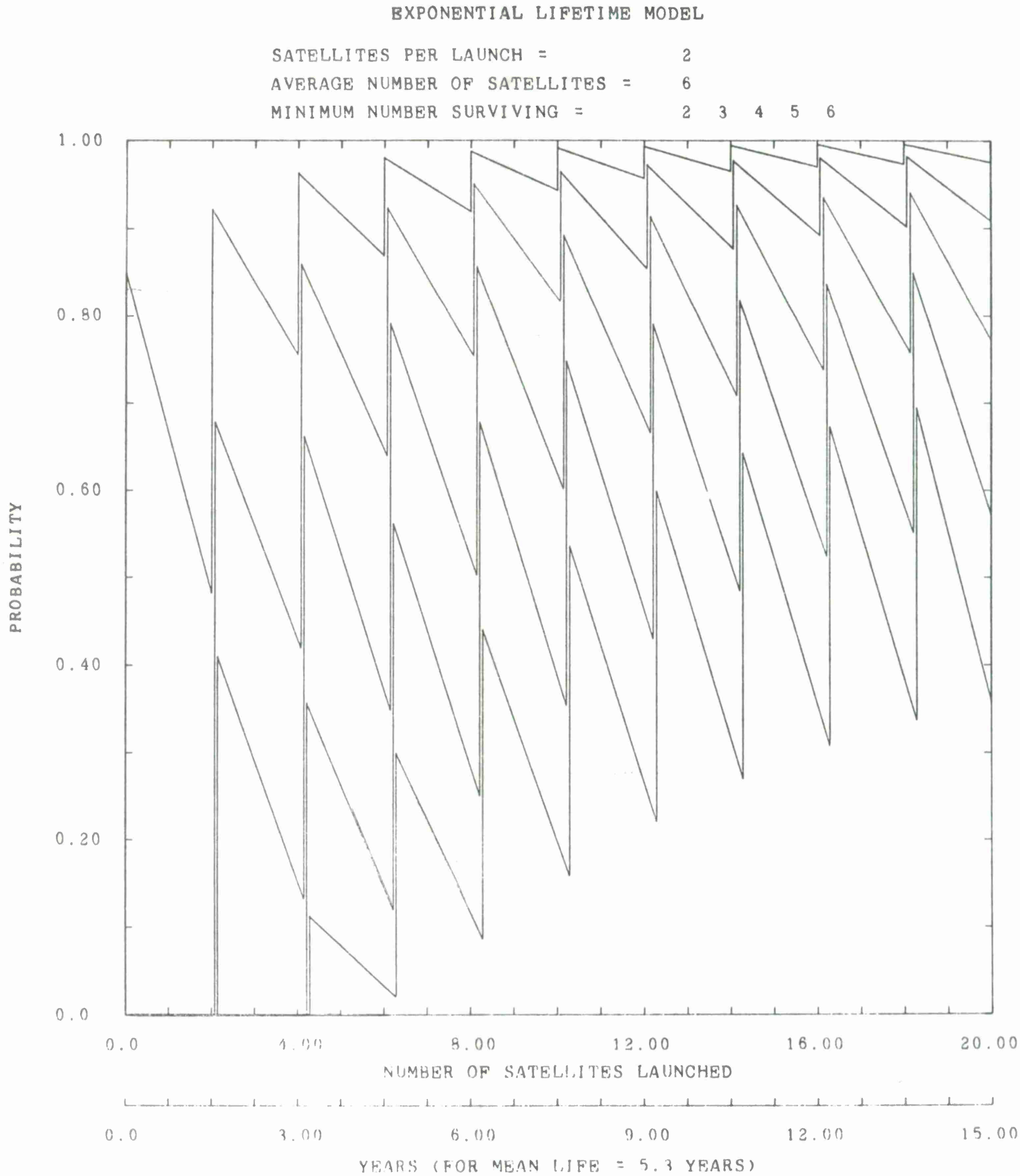
AVERAGE NUMBER OF SATELLITES = 4

MINIMUM NUMBER SURVIVING = 1 2 3 4





LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 2
AVERAGE NUMBER OF SATELLITES = 4
MINIMUM NUMBER SURVIVING = 1 2 3 4
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
4.50
9.00
13.50
18.00
22.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)


EXPONENTIAL LIFETIME MODEL
SATELLITES PER LAUNCH = 2
AVERAGE NUMBER OF SATELLITES = 6
MINIMUM NUMBER SURVIVING = 2 3 4 5 6
PROBABILITY
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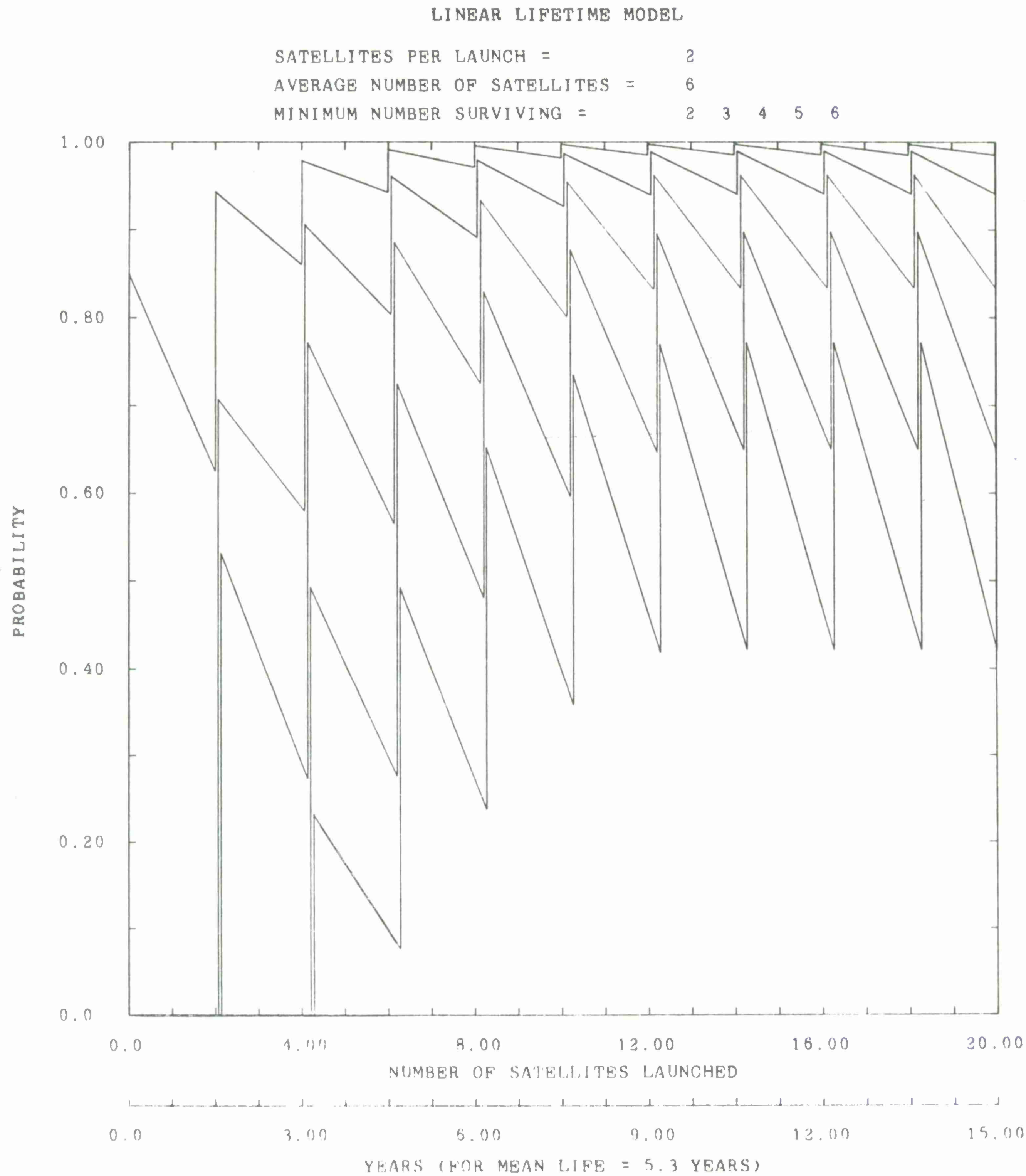
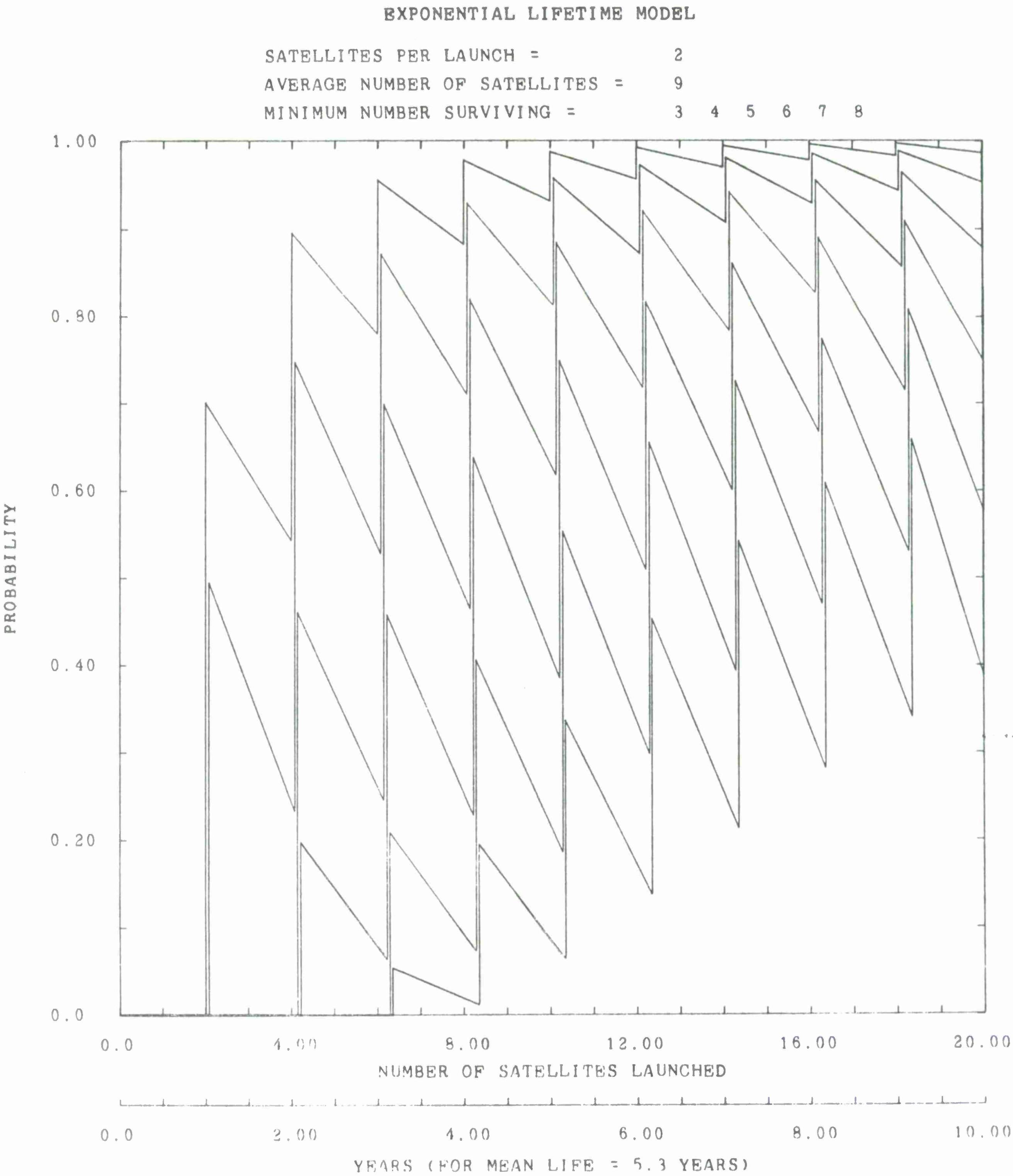
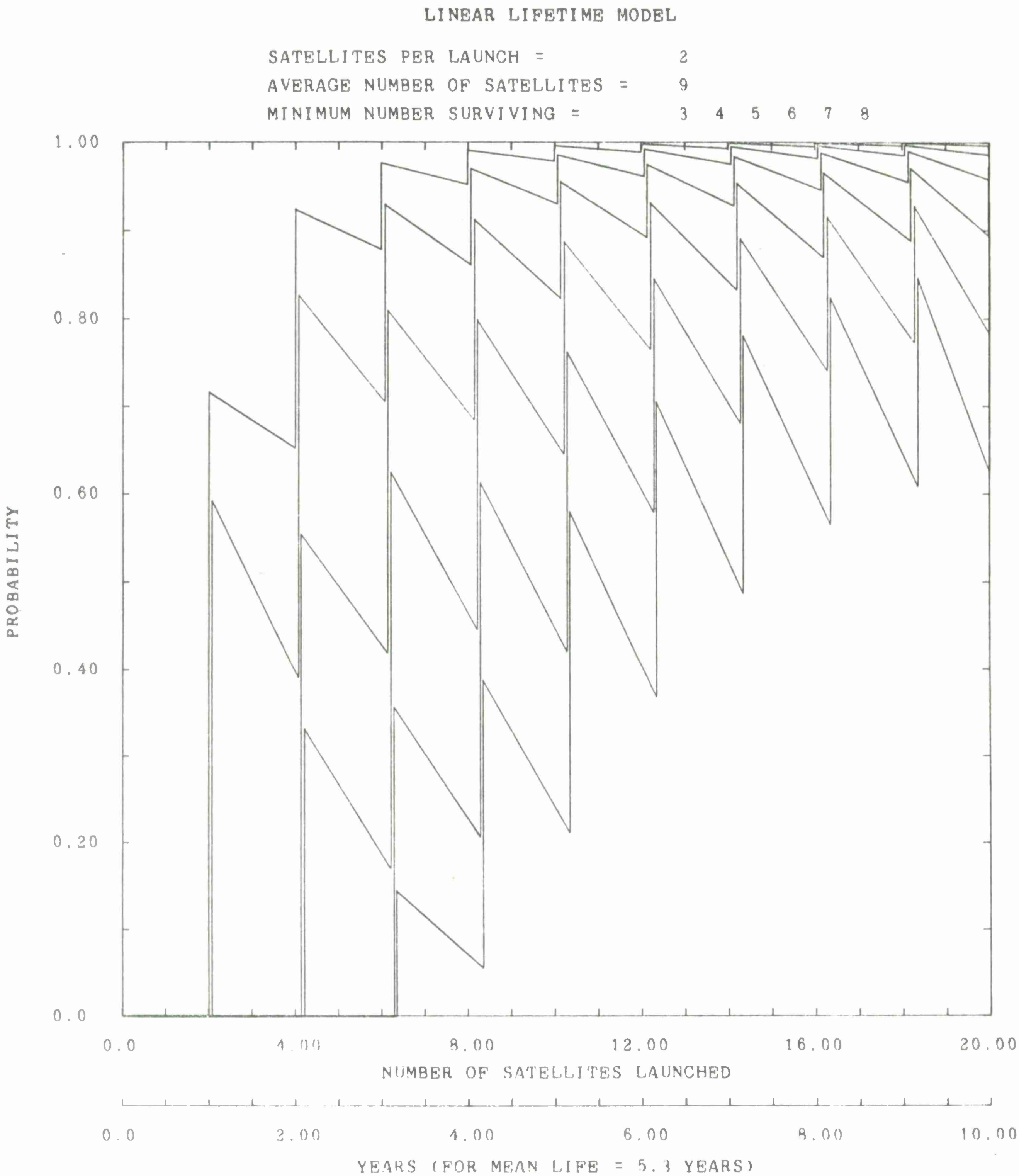
0.80
0.60
0.40
0.20
0.0
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
3.00
6.00
9.00
12.00
15.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)

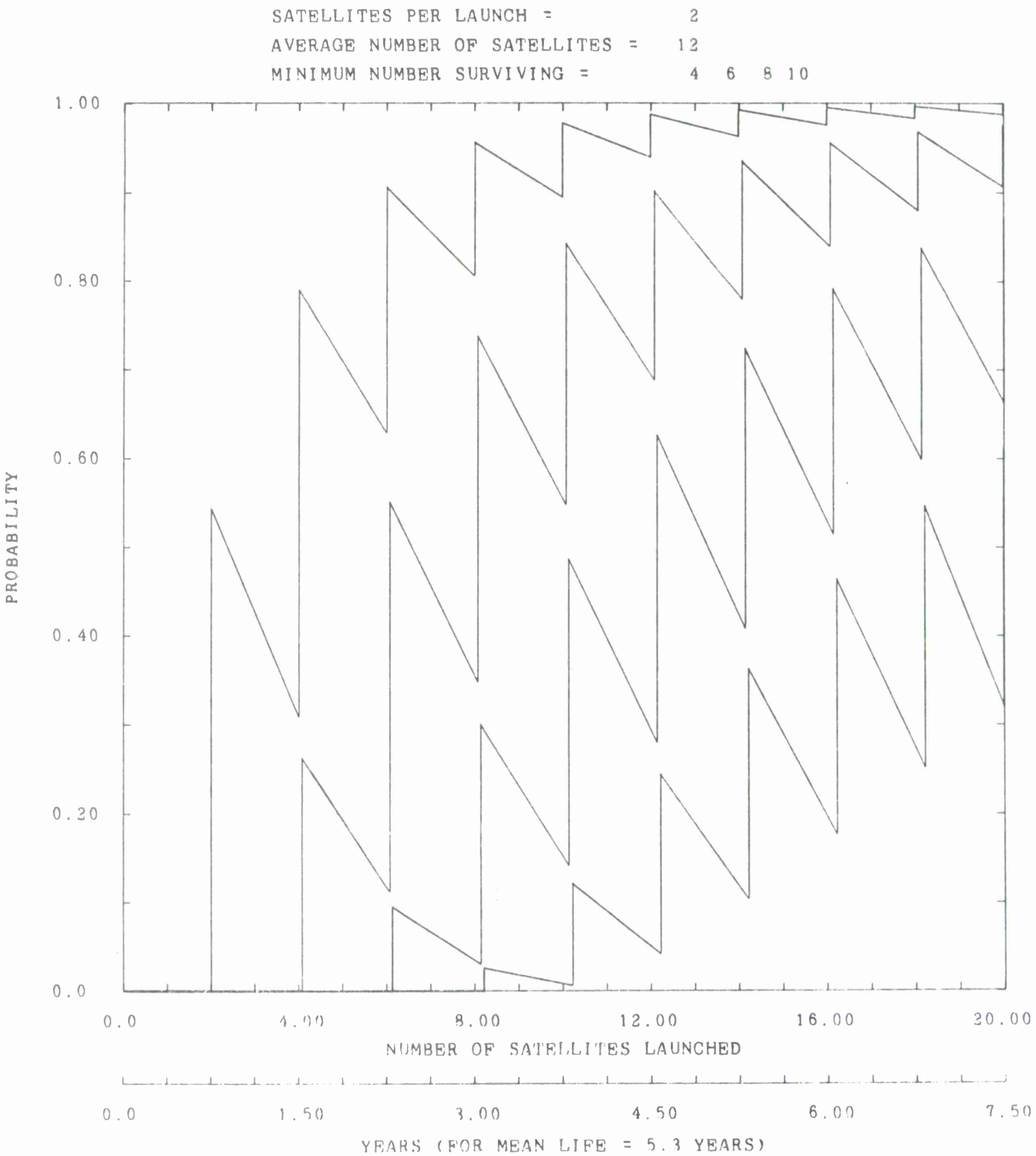


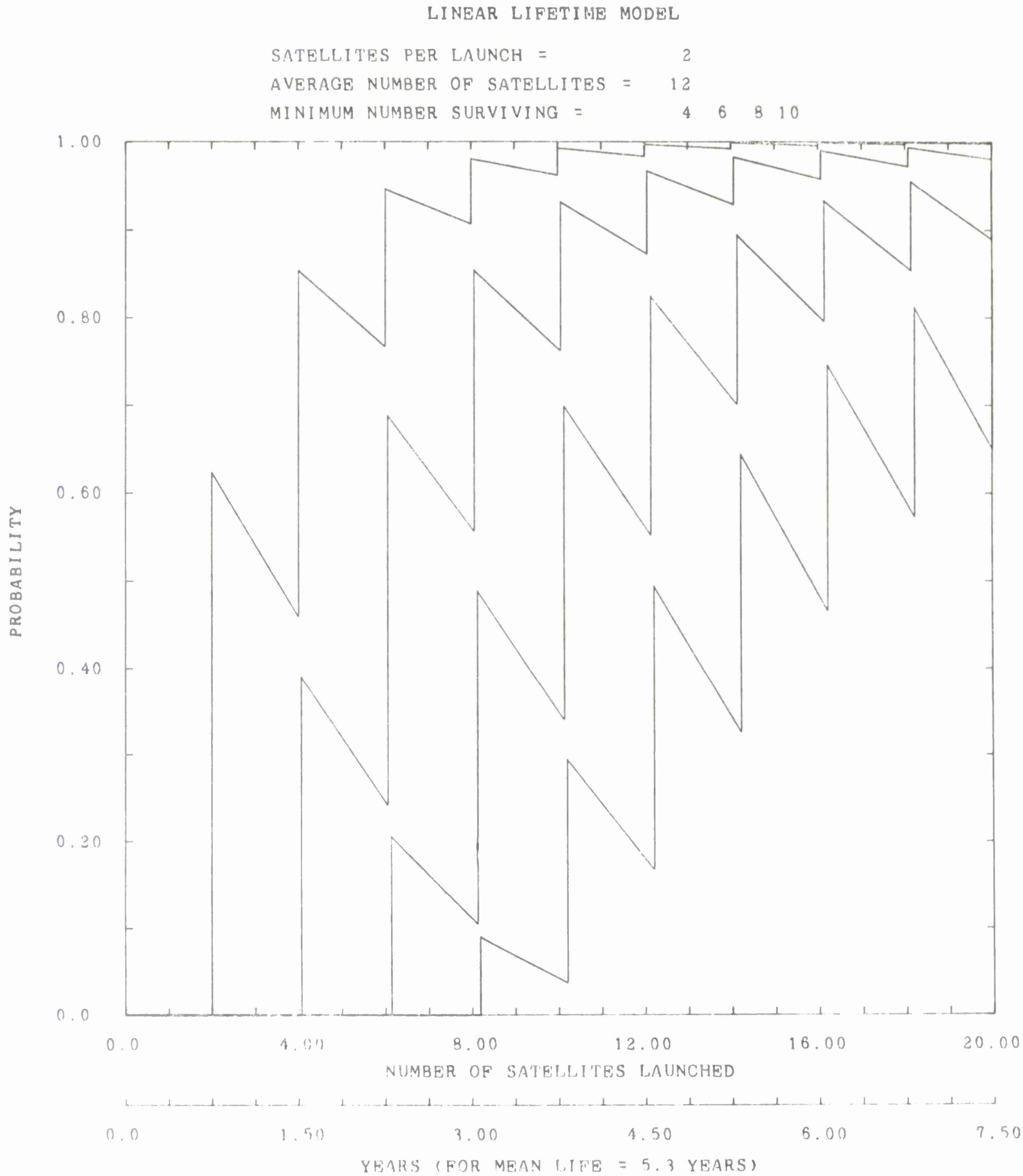
LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 2
AVERAGE NUMBER OF SATELLITES = 6
MINIMUM NUMBER SURVIVING = 2 3 4 5 6
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
3.00
6.00
9.00
12.00
15.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)


EXPONENTIAL LIFETIME MODEL
SATELLITES PER LAUNCH = 2
AVERAGE NUMBER OF SATELLITES = 9
MINIMUM NUMBER SURVIVING = 3 4 5 6 7 8
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
2.00
4.00
6.00
8.00
10.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)

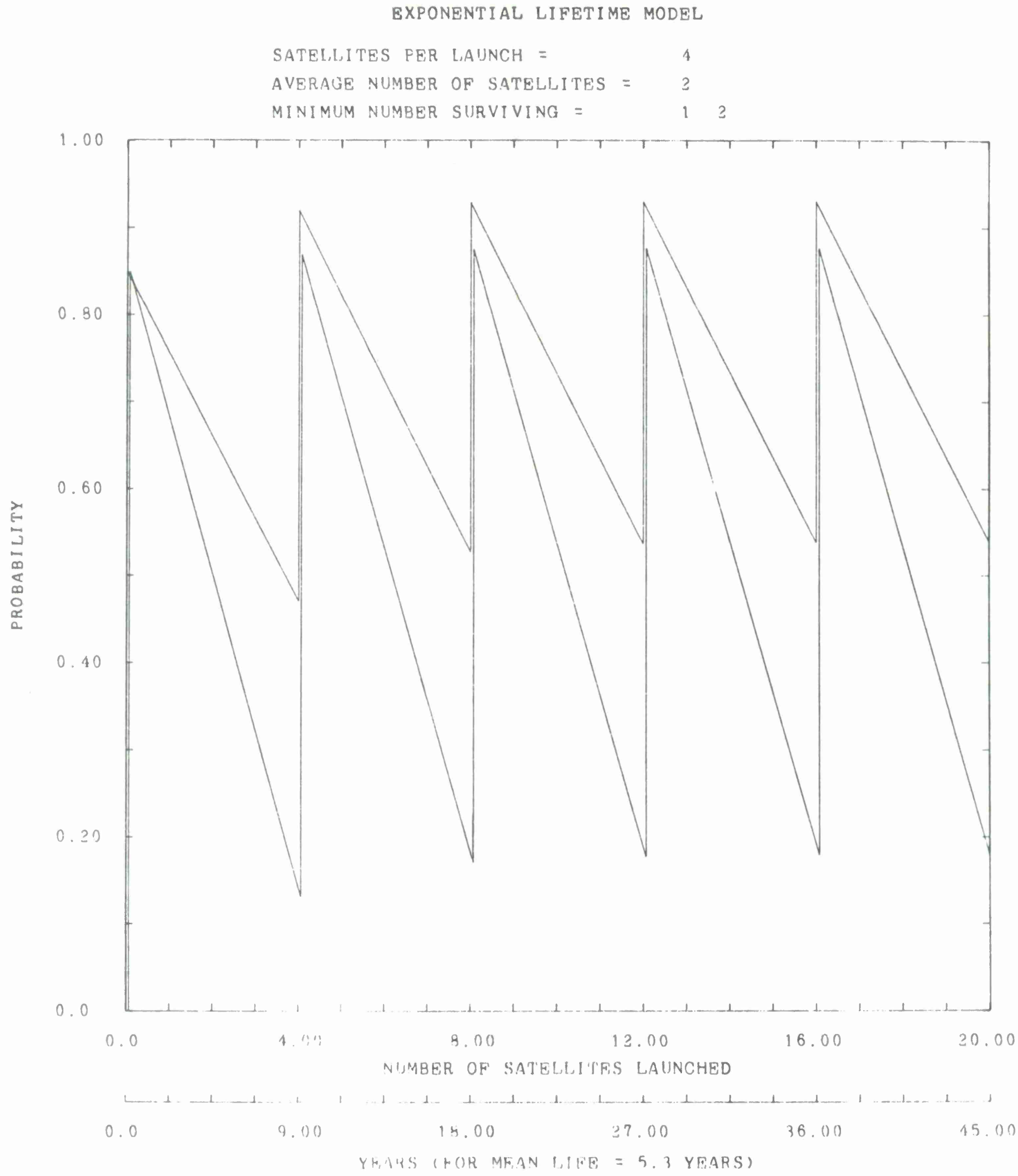

LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 2
AVERAGE NUMBER OF SATELLITES = 9
MINIMUM NUMBER SURVIVING = 3 4 5 6 7 8
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
2.00
4.00
6.00
8.00
10.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)

EXPONENTIAL LIFETIME MODEL





LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 2
AVERAGE NUMBER OF SATELLITES = 12
MINIMUM NUMBER SURVIVING = 4 6 8 10
1.00
0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
1.50
3.00
4.50
6.00
7.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)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MINIMUM NUMBER SURVIVING = 1 2
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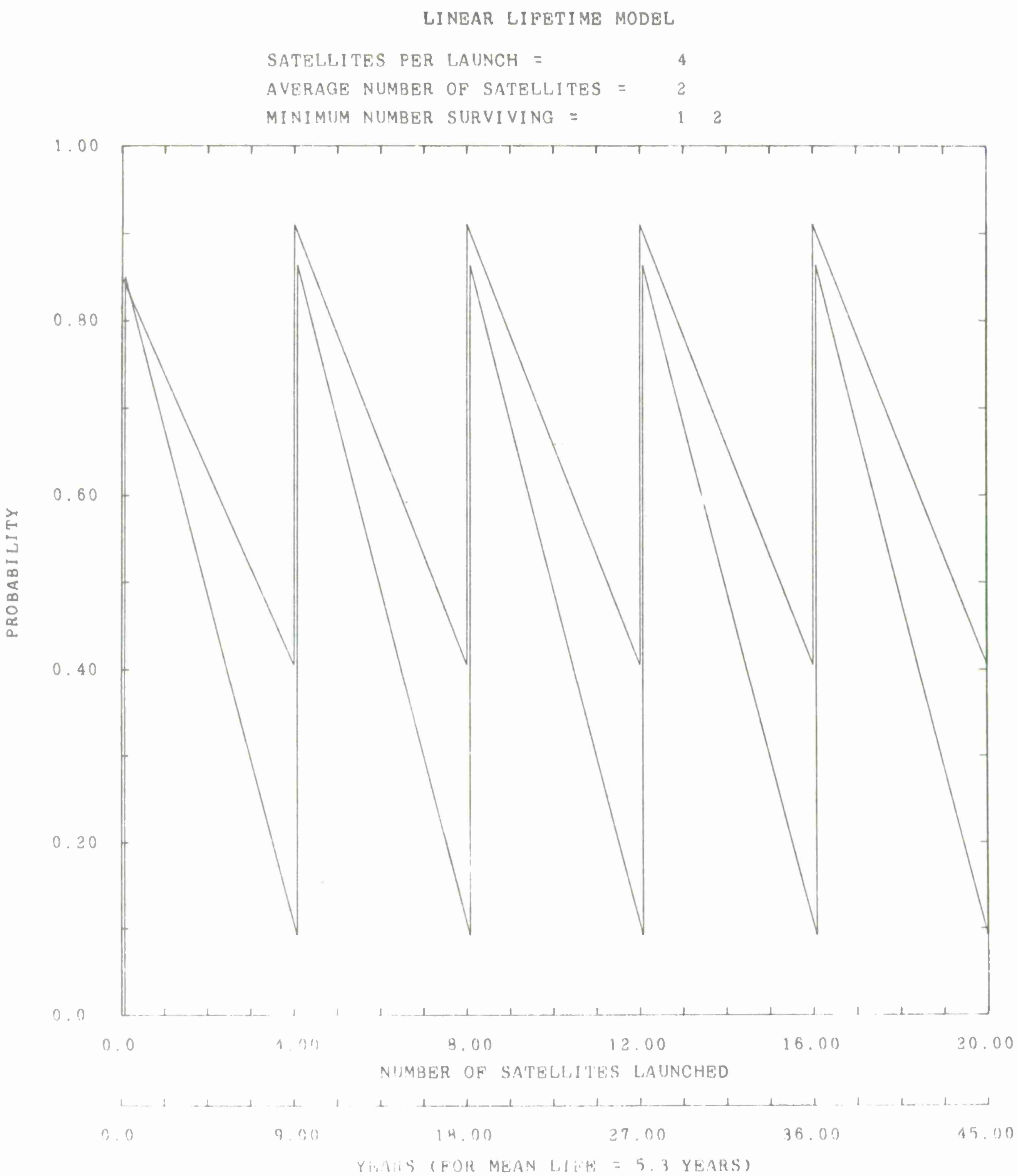
1.00
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
9.00
18.00
27.00
36.00
45.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)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MINIMUM NUMBER SURVIVING = 1 2
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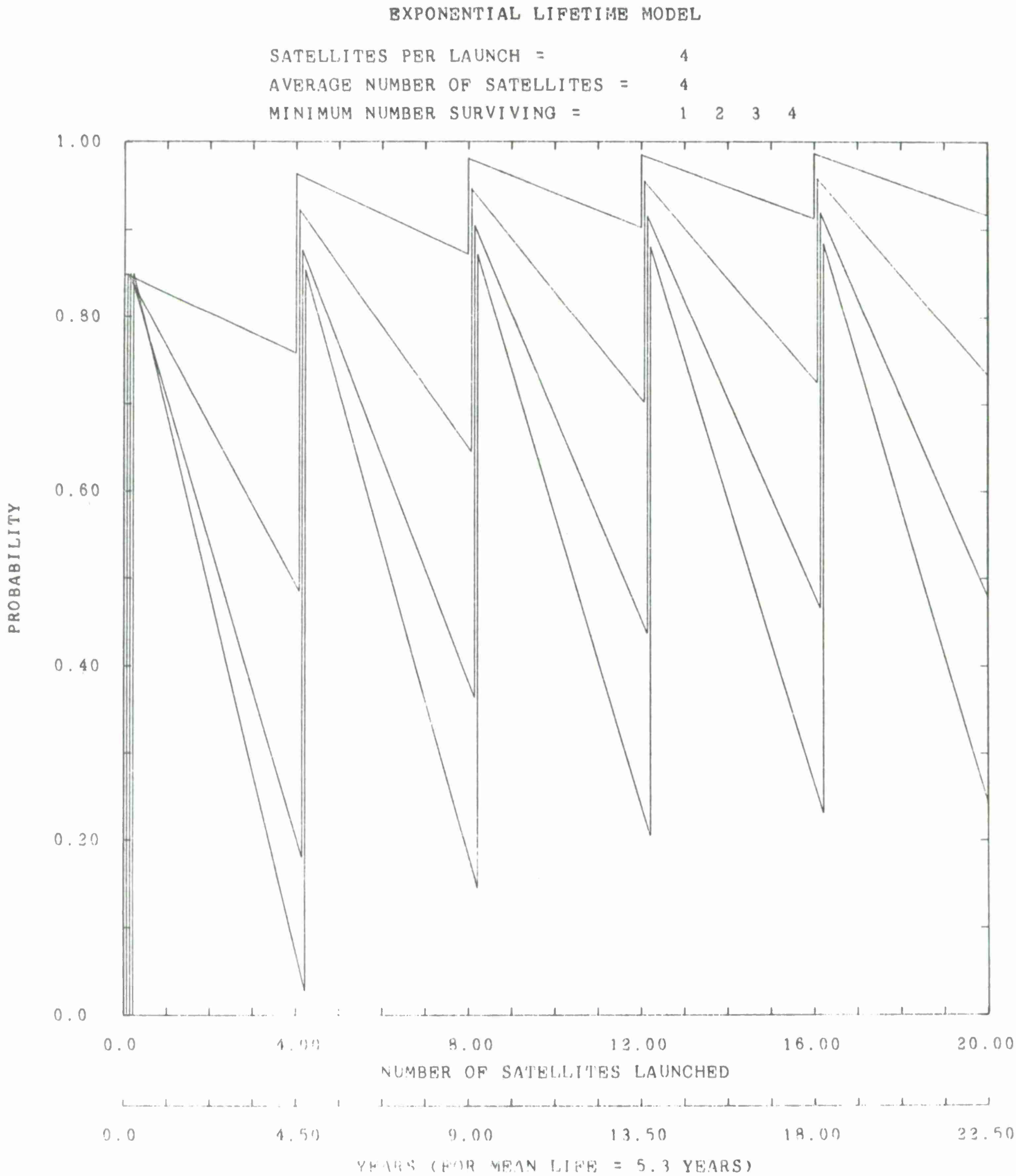
0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
18.00
27.00
36.00
45.00
(FOR MEAN LIFE = 5.3 YEARS)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0.80
0.60
0.40
0.20
0.0
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
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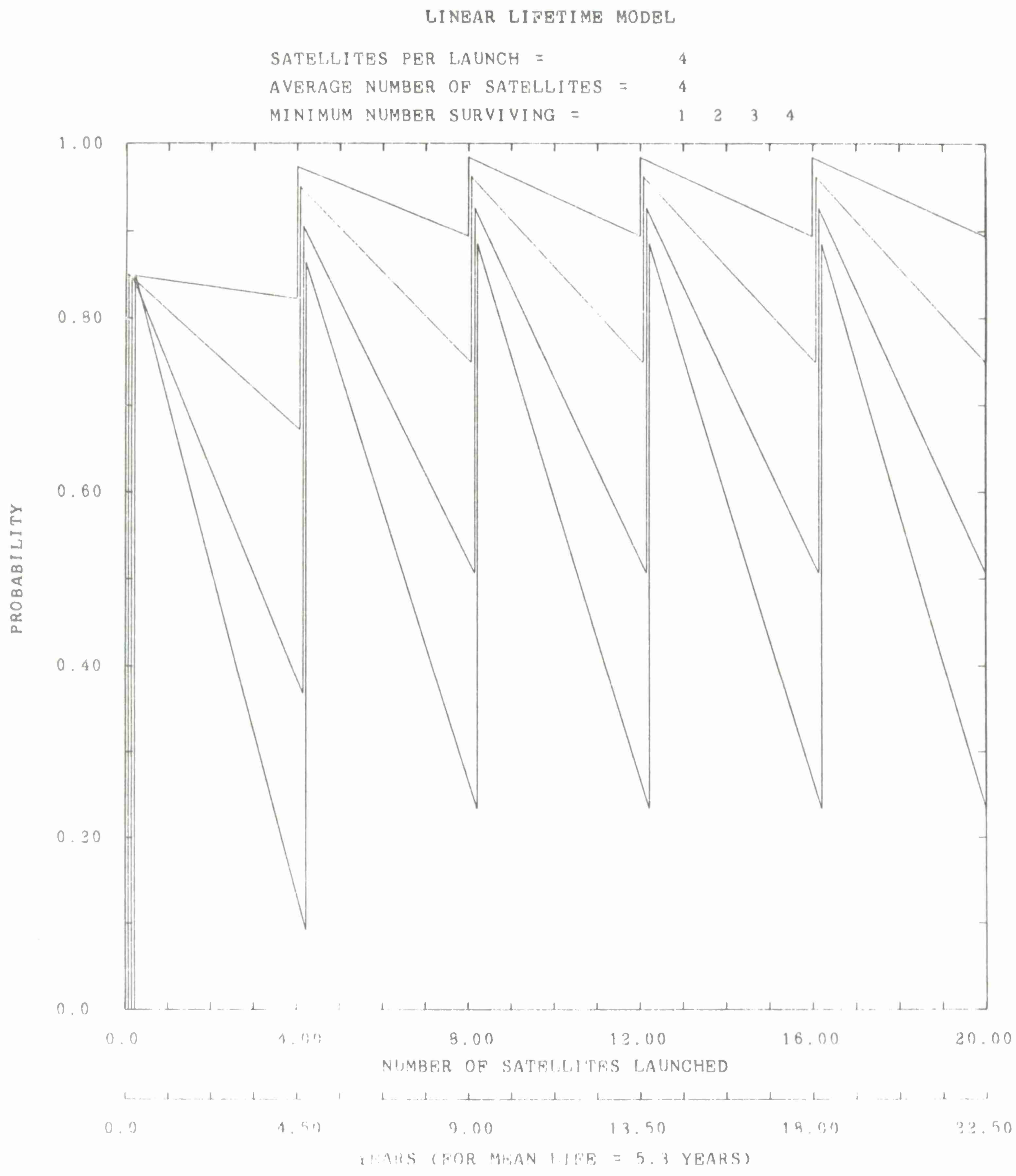
9.00
13.50
18.00
22.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)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MINIMUM NUMBER SURVIVING = 1 2 3 4
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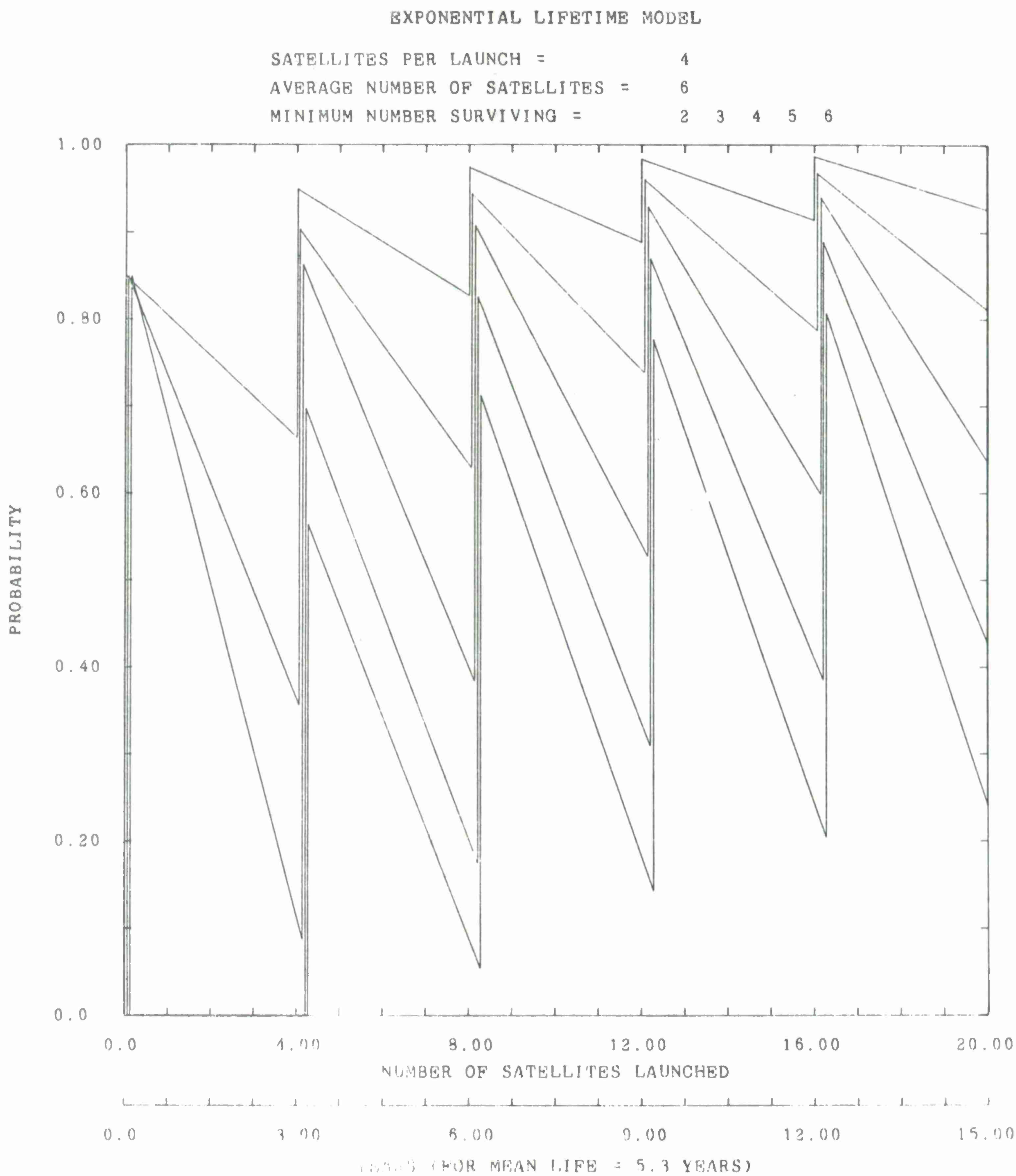
0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
4.50
9.00
13.50
18.00
22.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)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8.00
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NUMBER OF SATELLITES LAUNCHED
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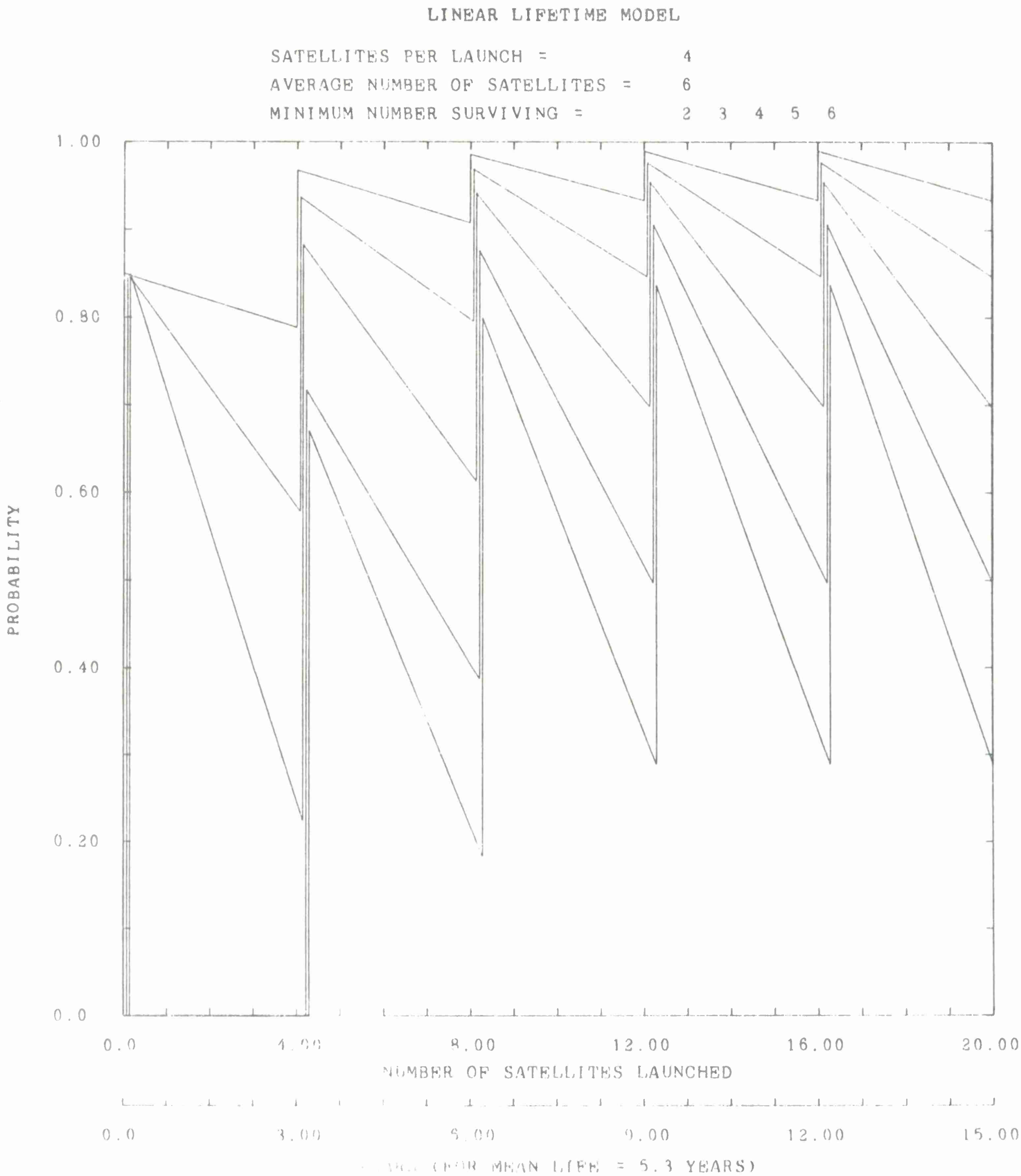
(FOR MEAN LIFE = 5.3 YEARS)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MINIMUM NUMBER SURVIVING = 2 3 4 5 6
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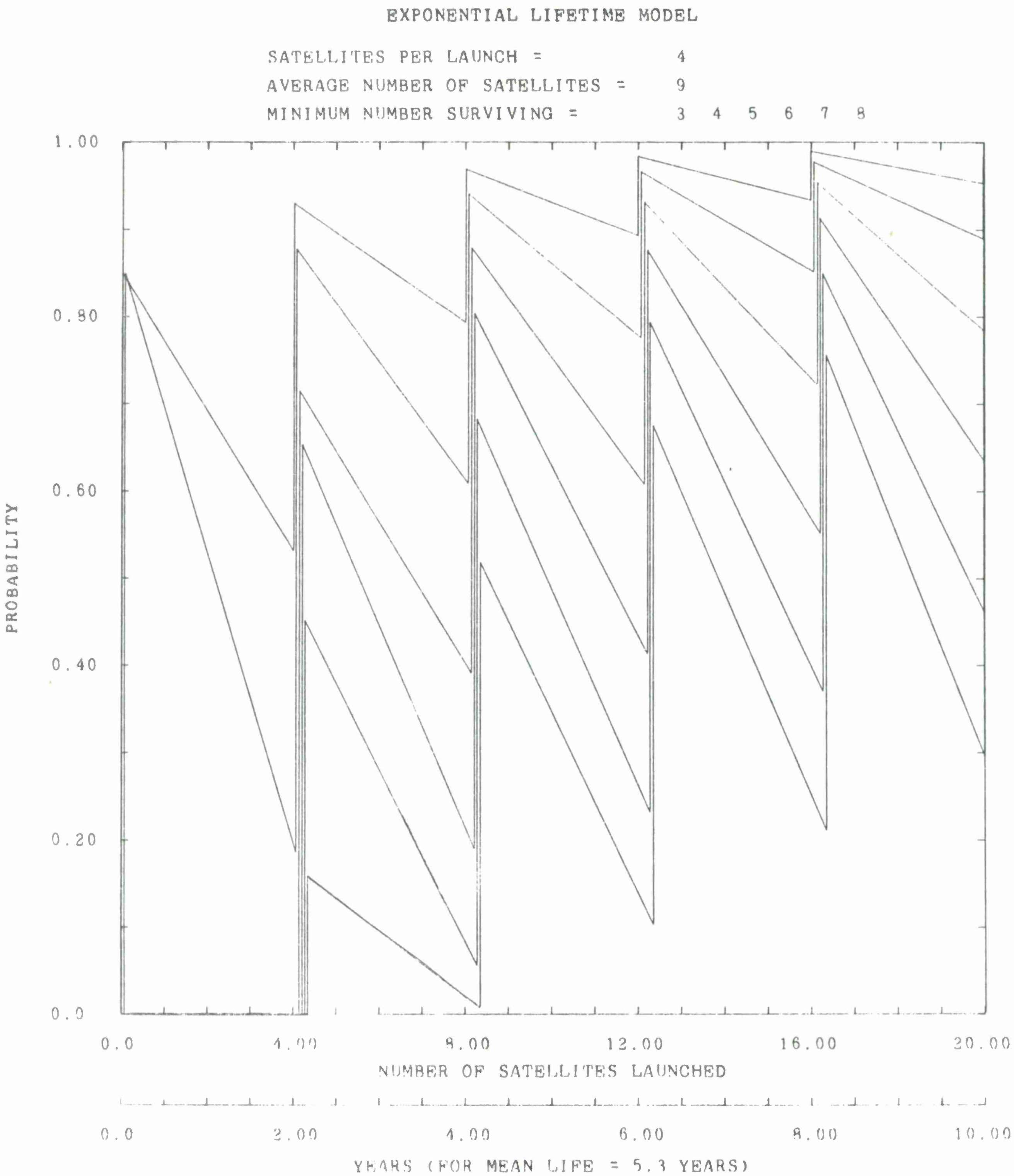
0.80
0.60
0.40
0.20
0.0
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
9.00
12.00
15.00
(FOR MEAN LIFE = 5.3 YEARS)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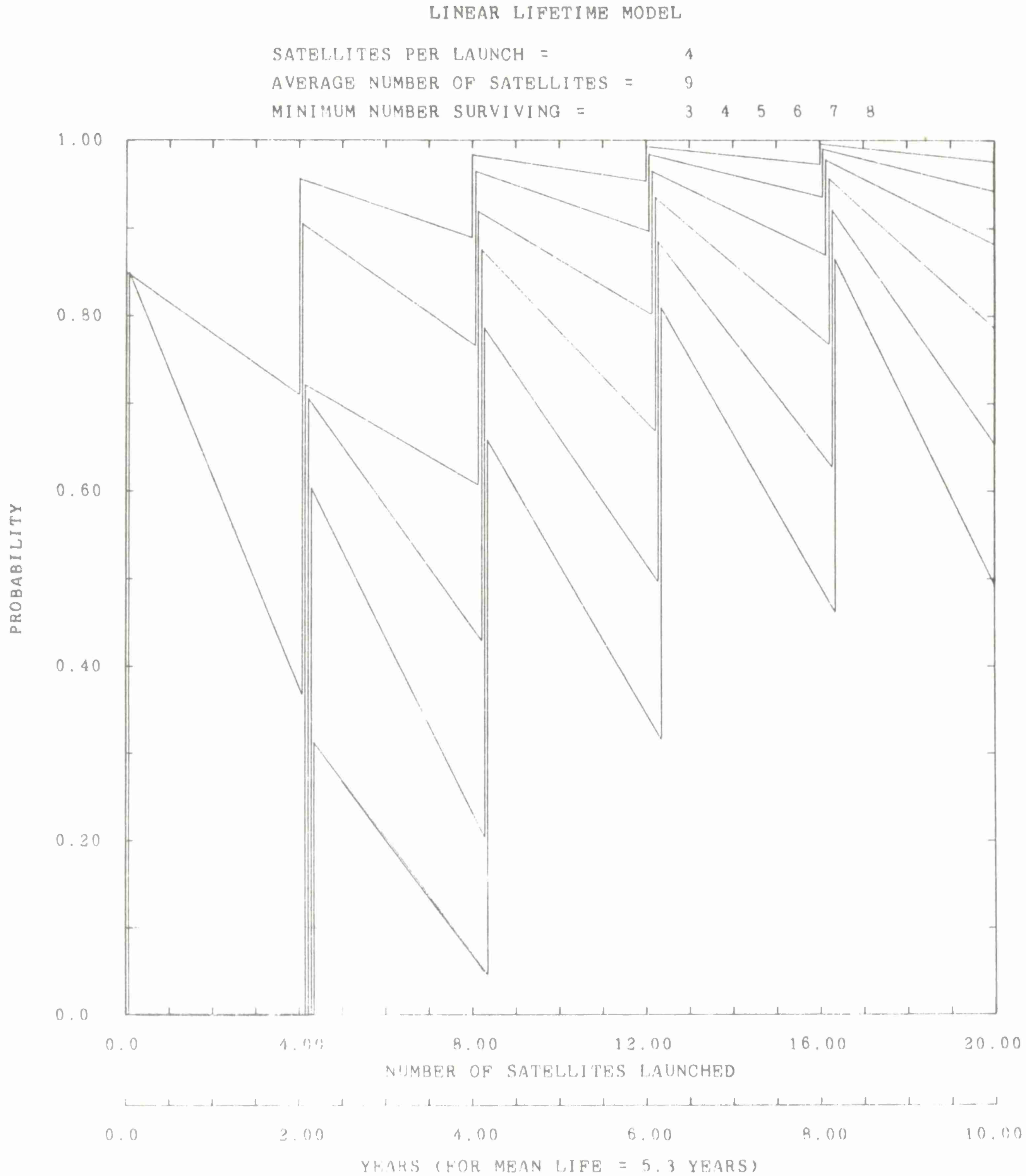
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
2.00
4.00
6.00
8.00
10.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)



LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 4
AVERAGE NUMBER OF SATELLITES = 9
MINIMUM NUMBER SURVIVING = 3 4 5 6 7 8
PROBABILITY
1.00
0.80
0.60
0.40
0.20
0.0
0.0
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
4.00
6.00
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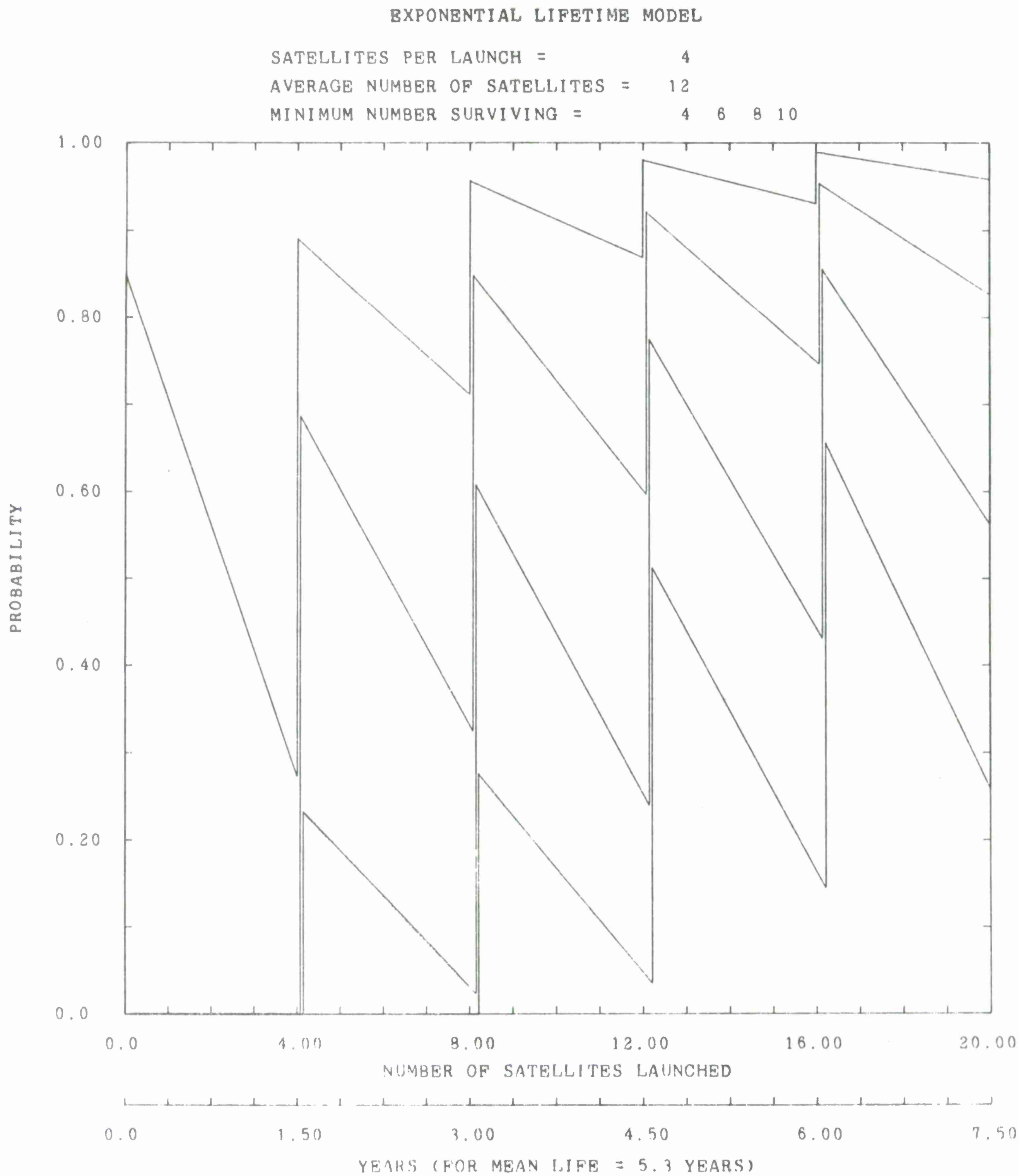
10.00
YEARS (FOR MEAN LIFE = 5.3 YEARS)


EXPONENTIAL LIFETIME MODEL
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AVERAGE NUMBER OF SATELLITES = 12
MINIMUM NUMBER SURVIVING = 4 6 8 10
PROBABILITY
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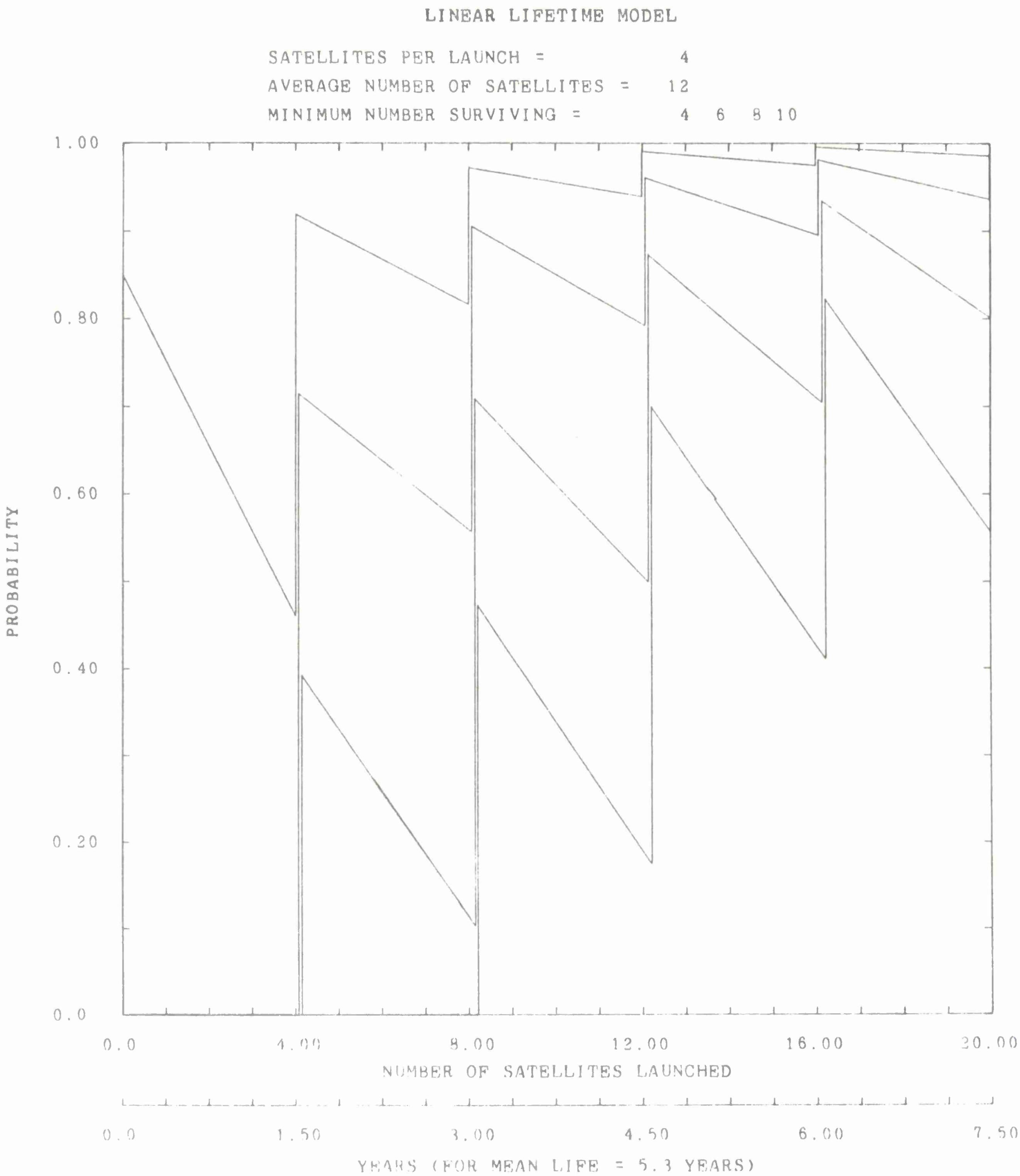
0.80
0.60
0.40
0.20
0.0
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
1.50
3.00
4.50
6.00
7.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)



LINEAR LIFETIME MODEL
SATELLITES PER LAUNCH = 4
AVERAGE NUMBER OF SATELLITES = 12
MINIMUM NUMBER SURVIVING = 4 6 8 10
1.00
0.80
0.60
0.40
0.20
0.0
PROBABILITY
0.0
4.00
8.00
12.00
16.00
20.00
NUMBER OF SATELLITES LAUNCHED
0.0
1.50
3.00
4.50
6.00
7.50
YEARS (FOR MEAN LIFE = 5.3 YEARS)

VI. CONCLUSIONS

The curves presented in Sec V show clearly that a launch plan based simply on setting η (the average number of satellites surviving) equal to the minimum number of satellites required for acceptable services, A, will in fact meet the service requirements with only low probability. In fact, even a 50% increase ($\eta = 1.5A$) in the average number of satellites results in dips in availability which may be unacceptable. High availability (>0.9) requires approximately a 100% increase in η, (i.e., $\eta = 2A$). The parameter of interest is η, since η determines the rate at which satellites must be acquired, and hence replenishment costs.

The lowest availability obviously takes place just before the next launch; the amount of dip taken depends primarily on the ratio of T/τ (time between launches to mean life time). Thus, for the same value of η, greater fluctuations in availability take place for larger m (satellites per launch vehicle) since T/τ increases with m. This means that the η required for acceptable service will be minimized by single launches. In particular, this raises the issue of how the large payload of the space shuttle can be utilized for replenishment of communications satellites.

Finally, it is very apparent from the curves that the start-up transient at the introduction of a new satellite lasts a substantial time. That is, availability of the system rises rather slowly to its "steady-state" value; a time period of at least 2τ must pass before this happens. Since τ is typically 5 years, availability will be significantly less than desired for a long time. This suggests that an initial launch rate significantly higher than the steady-state launch rate will be necessary to achieve acceptable service rapidly. On the other hand, if the new satellite design is replacing an already existing satellite system that has achieved an adequate availability, then launches at the rate required to maintain this steady-state availability will probably be adequate.

As an example of these facts, consider a series of dual launches every 1.5 years with a mean satellite life of 5.3 years. The average number of satellites surviving (in steady-state) is $\eta = 6$. If the system needs at least 4 satellites working to provide complete coverage, availability falls to 83% (linear life model) or 78% (exponential life model) just before a scheduled launch. A minimum availability of 70% is not reached until 9 years after launches begin (exponential life model) or after 4.5 years (linear life model). In contrast, if $\eta = 9$ (dual launches every 12 months) the steady state availability is greater than 95 % , and an 80% availability is reached after 4 years. To reduce the time to reach 80 % availability to 2.25 years, $\eta = 12$ must be used (dual launches every 9 months).

If single launches are used instead of dual launches, the steady state availability for $\eta = 6$ increases to 85% from 78% (exponential life model) or to 91% from 83% (linear life model) so it is clear that single launches provide a significant benefit.

In conclusion, a strategy of launching only on the failure of an essential in-orbit satellite implies a minimum number of satellites launched, but implies a loss of availability for the time interval between failure and successful launch. A strategy of a fixed scheduled periodic launches as considered in this report implies more satellites launched, but provides higher availability. Maintaining spares in orbit and then launching only on the failure of an in-orbit spacecraft is perhaps the least costly solution with minimal impact on availability, but the analysis of this approach is more complex and has not been considered here.

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This report considers the scheduling of periodic launches of communications satellites in order to maintain a required level of system availability. Since satellite lifetimes can be described only statistically, availability is described by the probability of having at least "A" satellites operating in orbit as a function of time. The behavior of this probability is calculated for variations in launch rate (satellites per year), multiplicity of launch (satellites per launch vehicle), and satellite failure model. The transient in availability at the introduction of a satellite system is seen clearly in the data curves.

The data in this report can be used to choose a launch strategy which meets specified availability requirements and minimizes the number of satellites that must be procured and launched over a program lifetime.

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