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TITLE A SEQUENTIAL TRIGGER PROCEDURE FOR USE IN MONITORING NUCLEAR POWER PLANT EMERGENCY DIESEL GENERATOR RELIABILITY

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by

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1. BACKGROUND AND PURPOSE

The reliability of onsite emergency alternating current (ac) power supplies is a major factor in assuring acceptable safety at light-water-cooled nuclear power plants. The risk of severe core damage during station blackout accidents at a given plant is minimized if the reliability of the emergency diesel generators (EDGs) is maintained at a sufficiently high level.

The Nuclear Regulatory Commission's (NRC's) existing regulations (General Design Criteria 17 and 18, 10 CFR Part 50, Appendix A) establish requirements for the design and testing of both offsite and onsite electric power systems. These requirements are intended to reduce the probability of losing all ac power.

The NRC guidance for EDG selection, design, qualification and testing is currently provided in three documents: (1) Regulatory Guide 1.9, Revision 2, (2) Regulatory Guide 1.108, Revision 1, and (3) Generic Letter 84-15. The NRC has determined that an amendment to 10 CFR 50.63, "Station Blackout," is the appropriate means for imposing new requirements regarding EDG reliability[1]. This amendment would require licensees to test and monitor EDG reliability against performance-based criteria that indicate possible degradation from the EDG target reliability levels selected in accordance with specified station blackout duration. The amended rule would be accompanied by a corresponding revised Regulatory Guide 1.9, Revision 3[2].

1.1 Proposed Rule

In addition to EDG surveillance testing to start and load-run (as discussed in Ref. [2]), unplanned starts and load-runs will sometimes occur during normal operations. The combination of at least monthly surveillance tests and unplanned EDG start and load-run demands provide the necessary data for EDG performance-based monitoring.

The proposed rule and regulatory guide consists of the following fundamental elements: (1) establishment of EDG target reliability levels that would comport with the reliability levels assumed in a licensee's coping analysis for station blackout; (2) trigger values with respect to EDG failures to start and load-run which serve two purposes -- to provide a warning of EDG degradation, and to provide a basis for taking regulatory action when there is reasonable evidence from surveillance testing that EDG reliability has degraded below the selected target values; and (3) a reporting regime for EDG failures consistent with this performance-based approach.

The overall goal is to develop a method that maximizes the probability of detecting a significant decrease in EDG reliability while minimizing the probability of indicating a decrease when none has actually occurred (a false alarm). It is recognized that these are competing requirements.

In order to comply with 10 CFR 50.63, the minimum EDG reliability should be targeted at either 0.95 or 0.975 per nuclear unit consistent with the reliability levels assumed in the coping analysis for station blackout. The target reliability selected is denoted as R_T. In conformance with this selection, the proposed rule uses the following three criteria:

EARLY WARNING: If there are three failures in the last 20 demands for either an individual EDG or for all EDGs assigned to a nuclear unit, this is an early indicator of deterioration of EDG reliability. The NRC is to be notified, in writing, within 30 days of reaching the failure condition stating the cause(s) for this condition and providing the EDG failure history for the nuclear unit within the last 100 demands.

PROBLEM DIESEL: If there are 4 failures in the last 25 demands of an EDG, this is further indication of EDG reliability deterioration. Following corrective action, this EDG is to be subjected to accelerated testing per Regulatory Guide 1.9, Revision 3, to demonstrate effectiveness of corrective actions (i.e., 7 consecutive failure-free tests). A written report to the NRC is required within 30 days of reaching the failure condition, describing corrective actions, stating the cause(s) for this condition and providing the EDG failure history for the nuclear unit within the last 100 demands.

DOUBLE TRIGGER: If there are 5 failures within the last 50 demands and 8 failures within the last 100 demands (nuclear unit $R_T = 0.95$), or 4 failures within the last 50 demands and 5 failures within the last 100 demands (nuclear unit $R_T = 0.975$), then this is reasonable evidence that the EDG reliability level has degraded below the selected target. This condition constitutes non-compliance with the proposed rule (§50.63(a)).

For convenience, the early warning criterion will be denoted simply as 3/20, which we read as "3 failures in the last 20 demands." Similarly, the problem diesel criterion will be indicated as 4/25, while the double trigger criteria will be denoted as 5/50 and 8/100 or 4/50 and 5/100, respectively. In remaining sections of this report we will subsequently also refer to these criteria as the **proposed triggers**, which we often abbreviate simply (particularly in legends of graphs) as the **proposed** procedure.

We note here that these proposed triggers are so-called **fixed sample-size** triggers in that the number of prior demands is precisely identified as an integral part of the stated trigger procedures (e.g., 20, 25, 50, or 100 demands). Such triggers contrast with so-called **variable sample-size** triggers in which the precise number of demands given a trigger condition is **not** known in advance. The alternative triggers described in Section 3 are of the variable sample-size type.

1.2 Purpose

The purpose of this report is to assess the performance of the proposed triggers in a simulated operational environment and to describe and evaluate an alternative trigger procedure which improves the detection of EDG reliability degradation without increasing false alarms. In addition, this alternative trigger procedure is just as practical for use by licensees as the proposed triggers.

Section 2 describes the Monte Carlo simulation used to assess the performance of both procedures. The alternative trigger procedure is described in Section 3, and performance comparisons of both procedures are discussed in Section 4. Section 5 presents our conclusions from the study.

2. MONTE CARLO SIMULATION

We developed a Monte Carlo simulation for use in examining the performance of the proposed and alternative trigger procedures in a simulated use environment. The computer program was written in standard FORTRAN 77 and executed on both a Sun workstation using a SunOS operating system under a Sun FORTRAN compiler and a Macintosh IIfx using System 6.0.7 under an Absoft MacFortran/020 compiler.

2.1 Groundrules

For this initial simulation, we assumed 2 EDGs per nuclear unit, in which each EDG is routinely tested monthly and alternately from month-to-month. We also assumed that the monthly Bernoulli tests were conditionally independent of each other given the underlying reliability of each diesel. The target reliabilities were further assumed to apply to the average unit EDG reliabilities.

The proposed trigger values were applied as follows:

Trigger	Applies To
Early Warning (3/20)	Individual and all EDGs
Problem Diesel (4/25)	Individual EDGs
Double (5/50 and 8/100) or (4/50 and 5/100)	All EDGs

Thus, the early warning trigger is applied in three separate ways: to the test data for each individual diesel and the combined test data from both diesels. The problem diesel trigger is applied separately to the test data for each individual diesel, while the double trigger is applied only to the combined test data from both diesels.

Following a problem diesel trigger, the corresponding EDG is subjected to confirmatory accelerated testing until there are 7 consecutive failure-free tests prior to the next routine test on the diesel. All test results, including the confirmatory test results following a problem diesel trigger, are counted for the triggers.

Because we are interested in the length of time to first detect an EDG degraded reliability condition [the number of months that elapse before the degraded condition is first detected by the appropriate trigger(s)], we did not model the improvement in EDG reliability that the confirmatory testing is designed to produce. In other words, the confirmatory testing until 7 consecutive failure-free tests are obtained was performed under the same degraded EDG reliability condition that triggered the problem diesel condition in the first place. This was done in order to examine the performance of the double trigger in detecting EDG degradation which has not been corrected.

Each simulation replication consists of a maximum of 500 routine monthly tests on each diesel. Generally, we found that 500 tests are quite sufficient to first detect the levels of degradation we are interested in, including spurious false alarm detections in which no degradation has occurred.

Each replication continues until the desired triggers of interest have each occurred for the first time after which the current replication is terminated and a new replication is begun. For example, for a given EDG reliability level, if all three triggers are of interest, the first early warning condition may occur at month 5, the first problem diesel condition at month 11, and the first double trigger at month 17.

These values would be recorded for the corresponding triggers for this replication, after which a new replication begins.

For purposes of initializing the proposed triggers, each diesel is tested for 100 months (prior to month 1) at some specified initial reliability level, which we denote by R_I, which is taken to be the same for each diesel. Although 100 months is sufficient, this value may be changed as an input parameter for a given "run" of the computer program. Typical values used for R_I are 0.95, 0.975, and 0.99. The initial values of 0.95 and 0.975 correspond to the target reliability levels, while 0.99 roughly corresponds to the industry average EDG reliability to start and accept load upon demand.

The EDG degradation (the "shift" in reliability) for both diesels is programmed to occur at a specified month M_S. This value is likewise an input parameter for a given computer run. The program is written such that neither, one, or both EDGs experience a degradation in reliability at month M_S. A "two-diesel shift" occurs when the reliability of both diesels has shifted from their initial value, while a "single-diesel shift" occurs when the reliability of only one diesel has shifted. The reliability of both EDGs from month 1 through month M_S-1 is assumed to be equal to the specified initial reliability R_I.

The simulation was conducted using 10,000 replications. The corresponding sampling error was observed to be less than or equal to 0.01 for all probability calculations. For example, if the probability of detecting a shift in EDG reliability of a given magnitude by a certain number of months was calculated to be, say, 0.78, changing only the random number seed could change this computed output value by as much as 0.01 (between 0.77 and 0.79). This error is acceptably small; thus, 10,000 replications are sufficient.

2.2 Simulation Output

As mentioned above, for each replication we are interested in observing the first month after the EDG reliability degradation occurs in which the desired trigger condition(s) exist. We calculate and save the corresponding number of months after the shift occurs.

For example, suppose that $M_s = 20$; then, for a given trigger of interest, suppose that we have the following situation:

Rep 1: Observe month 25 -> Save 25 - 20 + 1 = 6 months
Rep 2: Observe month 23 -> Save 23 - 20 + 1 = 4 months
•
•
•
Rep 10,000: Observe month 27 -> Save 27 - 20 + 1 = 8 months

Because we are interested in rapidly detecting EDG reliability degradation, the appropriate random variable (rv) of interest is the number of months to first detect the degradation. On a given run of the computer program, we have 10,000 empirical observations of this rv from which we compute moments and quantiles of the distribution of this rv. We compute the sample mean, standard deviation, skewness, and kurtosis of this rv. Also, we compute selected quantiles using standard nonparametric techniques[3].

In this study, we are interested in the uncertainty inherent in detecting a given EDG reliability degradation and are **not** interested in simply the average (or mean) performance, such as the average number of months to detect a shift of a given magnitude. Thus, we compute the cumulative probabilities of detecting the degradation for a specified desired vector of months (as input to a given computer run). Because we are interested in studying rapid detection of degradation, we commonly specify 25 months; namely, months 1 through 15, 20, 25, 30, 35, 40, 45, 50, 60, 75, and 100. We then calculate the cumulative probability of detection for each of these specified months by counting the fraction of the 10,000 replications in which the first detection occurred no later than the specified month (i.e., by the desired month or earlier).

For example, suppose that we are interested in calculating the cumulative probability of detection (of a specified shift for a given trigger) at month 10, say. We count the total number of the 10,000 replications in which the first detection of this shift has been by month 10 (any month 1 through 10). For our example, suppose that this total is found to be 8,100. The point estimate of the desired cumulative probability is then simply this accumulated total divided by 10,000, and this would be reported as the cumulative probability of detecting the shift at month 10. In our case this probability is estimated to be 8,100/10,000 = 0.81.

We then plot these cumulative probabilities for each of the desired months to form a cumulative probability distribution associated with the rv **months to first detection after the shift occurs**, or, more simply, **months after shift occurs**. Section 4 contains many plots of such distributions. It is these cumulative probability of detection distributions which we will consider when we compare the performance of the alternative trigger procedure in Section 3 to the proposed trigger.

Appendix A contains a sample output from one run of the Monte Carlo simulation program described above.

2.3 Computer Program Software Reliability

The reliability of the Monte Carlo simulation program for estimating EDG cumulative probabilities of detection is assured by comparison with limited results for the proposed triggers given by Loftgren and Gregory[4] of Science Applications International Corporation (SAIC). Reference [4] contains the results of analyses directed at assessing the statistical performance characteristics of many different fixed sample-size trigger procedures similar to the proposed triggers. Only a single EDG is considered and the only cumulative probability of detection results presented in Ref. [4] are for the probability of detection at 50 demands.

Figure 1 gives the results for the comparative probability of detection by 50 months after the shift occurs from our Los Alamos National Laboratory (LANL) analysis and that of SAIC for the case of a single EDG. The results are plotted as a function of the EDG reliability degradation from R_I of 0.95 to level R given by the abscissa of the graph. A target reliability $R_T = 0.95$ is assumed. Results are provided for the corresponding early warning (3/20), problem diesel (4/25), and double (5/50 and 8/100) triggers. The corresponding results agree fairly well, the observed differences perhaps due to such things as the initialization procedure used and the role and use of confirmatory test results following a problem diesel condition. Based on these and similar other comparisons with Ref. [4], we conclude that the simulation program is reliably performing as intended.

3. SEQUFNTIAL TRIGGER PROCEDURE

The performance of the proposed triggers is quite sensitive to the initial reliability R_I prior to degradation. This is illustrated in Fig. 2 in which we have plotted the cumulative probability of detecting a two-diesel shift to reliability R = 90% when using the proposed 5/50 and 8/100 double trigger, for three different values of R_I, as a function of the number of months after the shift occurs. A target reliability $R_T = 0.95$ is also assumed. We observe that these probabilities are quite sensitive to the value of R_I. The detection probabilities are inversely proportional to R_I. Small values of R_I yield the largest detection probabilities because, in this case, there are more failures in the initial test data prior to the degradation thus allowing the double trigger condition to be more rapidly satisfied once the degradation occurs. A similar situation exists for the other proposed triggers as well.

It would be more desirable if the detection probabilities were less dependent on R_I. In this case the performance would be more uniform in industry-wide implementation of the triggers per the proposed rule. This shortcoming could be avoided by using a trigger procedure that doesn't automatically extend as far back in time. The question then becomes: Is there a trigger procedure which periodically recycles (i.e., resets, restarts, or reinitializes) in the sense that , once recycling occurs, **all** the past performance data are ignored and the trigger statistics begin anew? The answer is affirmative, as we will now see.

We also note that these alternative triggers generally have higher probabilities of more rapidly detecting degradation in EDG reliability without increasing the false alarm rates. Also, we will see that they are just as easy to use as the proposed triggers.

Martz[5] discussed the advantages and disadvantages of several alternative trigger procedures. A procedure first proposed by Wald[6] was ranked by Martz as a potentially more powerful leading contender to the proposed triggers.

Wald developed the notion and use of item-by-item sequential sampling based on the sequential probability ratio test (SPRT). It is well known that the use of these variable sample-size plans usually require less sampling for the same protection probabilities than corresponding fixed sample-size plans. In the EDG context considered here, this statement equates to more rapid anticipated detection of EDG reliability degradation than that of the proposed triggers.

Vesely et al[7] also developed an SPRT approach for monitoring component failure rates in nuclear power plants. Based on Monte Carlo simulation, they concluded that SPRT-based procedures can be quite effective in detecting unacceptably high component failure rates or unacceptable increases (shifts) in the failure rate. While their procedure is similar to the approach we consider here, it differs in two important aspects: (1) they use a more complicated set of criteria for establishing their control limits; and (2) they graphically implement their procedure in the form of a control chart, while we choose a simple tabular format.

The SPRT procedure was initially developed for lot-by-lot acceptance sampling, in which lots of some product are submitted to item-by-item sequential sampling. If the accumulated number of defective items in a sequential sample of size n exceeds a stated upper rejection limit, then the entire lot is rejected as having a defect (or failure) rate that is unacceptably large. On the other hand, if the accumulated number of defective items falls below a stated acceptance limit, then the entire lot is accepted as having a defect rate that is acceptably small. The acceptance and rejection limits are calculated by specifying four parameters which together determine a pair of desired risk criteria -- the so-called consumer and producer risks.

The performance-based statistic required for using these SPRT triggers is the cumulative (or total) number of EDG failures in n tests (or demands) as n increases month-to-month.

In the case of EDG testing, we have a continuous process as the data become continually available; thus, the notion and use of "lots", as required by Wald, is not present. In this case, the SPRT procedure can be modified in a straightforward way to incorporate **recycling** (restarting, re initialization, or resetting) as discussed by Lorden and Eisenberger[8]. The SPRT, when used with recycling, is similar to CUSUM testing, although the resulting control chart can be much different (Van Dobben de Bruyn[9] and Lucas[10]).

Recycling is a simple notion. Suppose that a lower acceptance limit has been established. If the cumulative number of EDG failures falls on or below this limit at some month N, say, then at month N + 1 the entire procedure is recycled. By recycling we mean that the SPRT procedure starts anew at month N + 1 as though month N + 1 is now month "1". Correspondingly, the cumulative number of failures is also reset to zero after month N. This notion will become more clear when we present and discuss the implementation of the specific SPRT triggers. Because of our particular notion and use of this lower limit as a recycling trigger, as opposed to an acceptable lot quality limit, we refer to the lower SPRT acceptance limit as the **recycling limit**.

On the other hand, if the cumulative number of EDG failures fails on or above the upper rejection limit, then the trigger condition is said to exist, thereby indicating a degradation in EDG reliability. For example, as for the proposed procedure, the SPRT early warning trigger procedure is used in conjunction with the test and operational data for each diesel separately as well as for the combined data. If the cumulative number of failures falls on or above the upper rejection limit for one or more of these early warning triggers, this is taken as an early warning indication that EDG degradation has occurred. In our particular EDG application of the SPRT procedure, we refer to the upper rejection limit as the **detection limit**, as it is this limit which indicates that a degradation in EDG reliability has in fact occurred.

The SPRT limits are determined based on four specified parameters -- α, β, p_0, and p_1. In the original Wald development, the α and β parameters represent Type I and Type II statistical errors, respectively, while p_0 and p_1 represent the quality levels (in terms of lot fraction defective) at which the Type I and Type II errors occur. Thus, p_0 is an acceptable quality level for which lots are to be accepted, while p_1 is an unacceptable quality level at which lots are to be rejected. It is thus required that p_1 must be larger than p_0. The pair (α, p_0) defines the so-called producer's risk point and the pair (β, p_1) defines the so-called consumer's risk point on the operating characteristic (OC) curve. However, because of the use of combination plans along with recycling, these designations no longer hold, and the four parameters no longer have this simple interpretation. Thus, we treat the four parameters as simply that -- four parameters that we must specify in order to define the SPRT procedure **without** any particular interpretation being attached to these parameters.

For the four specified parameters (α, β, p_0, p_1), the SPRT detection and recycling limits are given by

$$\begin{aligned} &\text{DETECTION LIMIT:} \quad D = A + Bn \\ &\text{RECYCLING LIMIT:} \quad R = C + Bn \end{aligned} \tag{1}$$

where

$$
\begin{aligned}
U &= \ln[p_1(1-p_0)] \\
V &= \ln[p_0(1-p_1)] \\
G &= U - V \\
A &= \ln[(1-\beta)/\alpha]/G \\
B &= \ln[(1-p_0)/(1-p_1)]/G \\
C &= \ln[\beta/(1-\alpha)]/G
\end{aligned}
\qquad (2)
$$

and where n denotes the number of EDG tests.

To illustrate this procedure, consider the SPRT problem diesel trigger. By employing the philosophy discussed below, the four specified parameters are found to be $\alpha = 0.05$, $\beta = 0.38$, $p_0 = 0.05$, and $p_1 = 0.20$. From (1) and (2) , the corresponding detection and recycling limits are given by D = 1.6158 + 0.1103n and R = -0.588 + 0.1103n, respectively. These limits are plotted in Fig. 3.

By using these limit equations, it is much simpler to implement the SPRT procedure by constructing a table of the detection and recycling values as a function of n over an appropriately large range of n. We have done this in Table 1 which is used as follows. If the cumulative number of failures in n tests is equal to or greater than the corresponding value in the column labeled **D** (for **Detection**), then a problem diesel condition is declared for the EDG for which the data apply and the SPRT procedure would be recycled at the next scheduled monthly test. If the cumulative number of failures in n tests equals or is less than or equal to the corresponding value in the column labeled **R** (for **Recycling**), then the procedure would simply be recycled at the next scheduled monthly test with no associated EDG declaration being made. If the cumulative number of failures in n tests falls within the **D** and **R** values, the SPRT procedure would likewise make no declaration (insufficient evidence for either a problem diesel condition or for recycling) and the procedure would simply continue by further accumulating next month's test results and comparing the new accumulated failure total to the tabled values at n+1.

We observe in Table 1 that detection of a problem diesel condition requires at least 2 EDG tests on a given diesel in which both tests are failures. There are, of course, many other pathways in which detection can occur. We also observe that recycling requires at least 6 EDG tests on a given diesel in which there are no failures. Although they do not affect the implementation of the SPRT trigger procedure, many of the values reported in Table 1 are superfluous. For example, it is not possible to recycle the procedure at n = 7 with 0 failures because the procedure will already have recycled at n = 6.

The confirmatory tests are not considered in the proposed SPRT procedures as 7 consecutive failures will often lead to recycling anyway. Thus, following a problem diesel condition, the accelerated test results are not considered in any of the proposed SPRT procedures and, if such testing is to remain a part of the proposed rule, the confirmatory test results are only exogenously used to ensure that a degraded EDG condition has been corrected.

The philosophy used to determine the SPRT triggers is as follows. Recall that the detection probabilities associated with the proposed triggers vary according to R_l. We choose to determine SPRT triggers (using Monte Carlo simulation as the appropriate tool) that closely match the two-diesel degradation false alarm distribution associated with the corresponding worse-case proposed trigger procedure. Recall from Fig. 2 that the highest false alarm probabilities occur for the smallest feasible value of R_l, i.e., when R_l is equal to the target reliability. Thus, we choose to match the false alarm distribution for two-diesel degradation when R_l is equal to the target reliability. This method assumes that the worse-case false alarm distributions associated with the proposed triggers are acceptably small and ensures that the SPRT triggers will not exceed the false alarm distributions of the proposed triggers. The required four parameters are found by a direct search method by observing the output cumulative detection probability distributions from the Monte Carlo program. It is hoped that the probability of rapidly detecting actual reliability degradation using the SPRT triggers will exceed that of the proposed triggers. That this is indeed the case will now be illustrated.

Figure 4 illustrates the comparative performance of both problem diesel trigger procedures for the case when R = 95% (false alarm detection probability distributions) and when R = 80% (significant degradation of EDG reliability) when both diesels degrade to these levels perhaps due to some common cause. When R_i is 0.95, we observe the close match in the false alarm distributions as desired. Although only 35 months of data are displayed in Fig. 4, the false alarm distributions continue to match through 100 months after the shift occurs. However, in this case, note that the SPRT procedure has higher probabilities of more rapidly detecting the shift in reliability to R = 80% than the proposed trigger. When R_i is 0.99 (closer to the industry average), the proposed trigger has significantly smaller false alarm probabilities and significantly smaller probabilities of rapidly detecting the shift to R = 80% than the corresponding SPRT procedure. Note that the performance of the SPRT trigger is less sensitive to the initial reliability as claimed earlier.

Applying this same philosophy in conjunction with (1) and (2) yields the following SPRT trigger parameters:

Trigger	α	β	p_0	p_1	A	B	C
Early Warning	0.15	0.28	0.05	0.20	1.0067	0.1103	-0.713
Problem Diesel	0.05	0.38	0.05	0.20	1.6158	0.1103	-0.588
Double (R_T = 0.95)	0.07	0.20	0.05	0.20	1.5635	0.1103	-0.986
Double (R_T = 0.975)	0.025	0.20	0.025	0.20	1.4756	0.0869	-0.548

The corresponding tabular format (analogous to Table 1) for easy use in implementing these SPRT triggers is given in Tables 2 - 4 for the remaining triggers. However, because the double triggers are only used in conjunction with the combined EDG test data, only the even values of n are required in Tables 3 and 4.

Although the tables are quite similar, a close examination reveals differences which significantly alter their performance. The performance of these SPRT triggers relative to the corresponding proposed triggers will now be illustrated.

4. PERFORMANCE COMPARISONS

In this section we compare the performance of the proposed and SPRT (sequential) double, problem diesel, and early warning triggers under various simulated use conditions. In particular, we consider R_l values of 0.95, 0.975, and 0.99; two-diesel and single-diesel degradation; step and ramp (gradual) degradation profiles; and the performance relative to the average unit EDG reliability. For convenience, we have included the important parameters in either the figure caption or on the figures themselves in all of the illustrations referenced in this section.

In order to compare the performance of both methods, we must choose a month M_s in which the reliability degradation occurs. The performance of neither trigger procedure significantly depends on the particular month in which the degradation (or shift) occurs; however, the SPRT sometimes does yield slightly less optimistic results if the shift occurs at month $M_s = 1$ (which is the startup month for the SPRT procedure). The reason for this is that insufficient "smoothing" occurs if $M_s = 1$, whereas if M_s is sufficiently greater than 1, the statistical characteristics associated with the recycling feature of the SPRT "smoothes" the procedure to the extent that the performance essentially becomes independent of M_s. This is illustrated in Fig. 5 for a typical SPRT trigger. Note that the probabilities for detecting a two-diesel shift to $R = 80\%$, and the corresponding probabilities of a false alarm, within the first 5 months after the shift occurs at month 1 are slightly below those obtained when the shift occurs at either months 4 or 20. In order that the SPRT procedure has had sufficient opportunity for "smoothing" to occur, in our simulation study we chose to introduce the EDG degradation arbitrarily at month $M_S = 20$; however, in a few cases we also chose $M_S = 1$.

4.1 Double Trigger ($R_T = 0.975$)

Figure 6 illustrates the effect of two different values of R_I on both double trigger procedures when $R_T = 0.975$ for detecting a two-diesel shift to the indicated reliability R. This figure shows the match used to determine the SPRT parameters. Note that the SPRT false alarm probabilities are slightly less than those for the proposed double trigger when R_I is 0.975. However, even in this case, the SPRT double trigger has significantly higher probabilities of detecting the indicated degradation in the first 10 months or so after the shift occurs.

Figures 7 and 8 illustrate the comparative results for detecting a two-diesel degradation to reliability R when R_I is 0.975 and 0.99, respectively. The SPRT procedure outperforms the proposed procedure in early detection of the degradation, particularly when R_I is 0.99. Note that, for large values of R, in the long run (after a sufficiently large number of months have elapsed after the shift) the proposed trigger has a higher probability than the SPRT trigger in ultimately detecting the degradation. However, because we are mainly interested in increased probabilities of early detection, this result detracts little from the practical gains associated with the SPRT procedure.

Similarly, Figs. 9 and 10 consider a single-diesel degradation to reliability R, and, as in the case of two-diesel degradation, the SPRT outperforms the proposed procedure in early detection of the degradation.

In Fig. 11 we compare the performance for detecting a degradation when both EDGs degrade to the same reliability level versus the case when the EDGs degrade to different levels, but with an average (mean) reliability which is approximately the same as the level to which both EDGs degraded. Although there are some differences between these two cases for each trigger procedure, the differences are rather insignificant.

4.2 Double Trigger ($R_T = 0.95$)

Figure 12 illustrates the effect of two different values of R_I on both double trigger procedures when $R_T = 0.95$ for detecting a two-diesel shift to the indicated reliability R. This figure shows the match used to determine the SPRT parameters. Note that the SPRT false alarm probabilities are somewhat less than those for the proposed double trigger when R_I is 0.95. The SPRT trigger has higher probabilities of detecting the shift to $R = 0.80$ by 10 or 15 months after the shift occurs regardless of the value of R_I.

Figures 13 - 16 correspond to Figs. 7 - 10 and similar results are obtained.

4.3 Problem Diesel Trigger

Now consider the comparative performance of both the proposed and alternative SPRT problem diesel triggers. Recall that Fig. 4 illustrates the effect of two different values of R_I on the performance of both trigger procedures when $R_T = 0.95$ for detecting a two-diesel degradation to $R = 0.80$ (a significant degradation) and $R = 0.95$ (a false alarm). Figure 4 thus illustrates the match used to determine the SPRT problem diesel parameters, thus identifying the SPRT procedure. The corresponding effect of two different values of R_I on the performance of both trigger procedures when $R_T = 0.975$ is illustrated in Fig. 17.

The comparative performances for detecting two-diesel degradation to reliability R are shown in Figs. 18 - 20 for initial reliabilities of 0.95, 0.975, and 0.99, respectively, while Figs. 21 - 23 give the same case for single-diesel degradation. As in the case of the double triggers, the SPRT trigger is observed to be superior for early detection of the indicated degradation without a significant increase in the false alarm probabilities.

The only type of EDG degradation considered thus far has been of the **step** variety. That is, the degradation to level R immediately occurs at month $M_s = 20$ in the form of a step function. We also consider another pattern of degradation, which we denote as **ramp** degradation. By ramp degradation we mean that the degradation begins month M_s at the R_I level and linearly degrades to level R by some specified period of months later (we consider periods of 3, 6, 12, and 18 months). Thus, ramp degradation models the situation where the degradation in EDG reliability is gradual and constant from month-to-month, due to some persistent cause which continually increases in intensity.

Figures 24 - 26 illustrate the comparative results obtained for detecting two-diesel degradation to R = 0.80 for both step and ramp patterns of degradation for respective R_I values of 0.95, 0.975, and 0.99. In all cases the degradation was assumed to begin starting at month 1. In the early months (less than 10 months), the proposed trigger generally outperforms the SPRT trigger when R_I is 0.95, while the opposite is true as R_I increases. When R_I is 0.99, the SPRT performance is excellent relative to the proposed trigger.

4.4 Early Warning Trigger

Figure 27 illustrates the effect of two different values of R_I on both early warning trigger procedures when $R_T = 0.95$ for detecting a two-diesel shift to the indicated reliability R. As before, this figure illustrates the match used to determine the SPRT early warning parameters, thus identifying the procedure. Again, we observe the rather significant sensitivity of the performance of the proposed trigger to R_I, while the performance of the SPRT trigger is less sensitive to this value.

The performance of both trigger procedures in detecting two-diesel degradation to reliability R for R_I values of 0.95, 0.975, and 0.99 is displayed in Figs. 28 - 30, respectively. As in the case of the other triggers, the SPRT significantly outperforms the proposed early warning trigger as R_I increases.

Similarly, Figs. 31 - 33 illustrate the comparative results for detecting single-diesel degradation to reliability R for the same three values of R_I. As before, the SPRT trigger outperforms the corresponding proposed trigger.

5. CONCLUSIONS

We have presented an alternative trigger procedure for use in detecting EDG reliability degradation based on performance data. This new procedure is based on the use of the Wald sequential SPRT. These SPRT triggers are just as easy to use as the proposed triggers. Based on our simulation results, we conclude that the variable sample-size SPRT triggers (1) are generally more powerful for rapid detection of EDG reliability degradation than the proposed fixed sample-size triggers without significantly increasing the false alarm detection probabilities; and (2) have probabilistic performance characteristics which are less dependent on the initial EDG reliability value(s) (prior to degradation) than the proposed triggers. Also, unlike the proposed triggers, the SPRT triggers require no past data for their initial implementation. They can be implemented beginning at month 1 using only the EDG test results for that month.

Finally, because of the notion and incorporation of recycling as an integral part of the SPRT procedure, there is no need to maintain and use long past histories of EDG test results as in the case of the proposed triggers in which as much as 100 months of past test results may be needed. Thus, the important question regarding the relevancy of such distant past data in determining the reliability of today's diesels becomes moot. As a consequence of this, the SPRT triggers may be more acceptable to the licensees.

For these reasons, we believe that the SPRT triggers should be adopted in the proposed rule change instead of the proposed triggers.

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APPENDIX. SAMPLE COMPUTER CODE OUTPUT

RELIABILITY SIMULATION OF TWO EMERGENCY DIESEL GENERATORS
CONSIDERING BOTH FIXED AND VARIABLE SAMPLE SIZE TRIGGERS

DATE: 9/14/92
SECONDS AFTER MIDNIGHT: 30736

STEP DEGRADATION FOR BOTH DIESELS - DOUBLE TRIGGER
STEP TO R1 = 0.80 AT MONTH 20 FOR DIESEL 1
STEP TO R2 = 0.80 AT MONTH 20 FOR DIESEL 2

RUN IDENTIFICATION NUMBER = RUN 233

FIXED SAMPLE-SIZE TRIGGERS
EARLY WARNING TRIGGER: 3/20
PROBLEM DIESEL TRIGGER: 4/25
CONFIRMATORY FAILURE-FREE TESTS: 7
DOUBLE TRIGGER: 5/50 AND 8/100

VARIABLE SAMPLE-SIZE TRIGGER CRITERIA
ALPHA = .070, P0 = .050
BETA = .200, P1 = .200

RELIABILITY TARGET = .950

500 MONTHS OF TWO-DIESEL TESTS ARE SIMULATED

INITIALIZED WITH 100 MONTHS OF TESTING AT RELIABILITY .950

200 MAXIMUM CONFIRMATORY PROBLEM DIESEL TESTS

EDG RELIABILITY FUNCTIONS
DIESEL 1: .950 PRIOR TO MONTH 20; .800 THEREAFTER
DIESEL 2: .950 PRIOR TO MONTH 20; .800 THEREAFTER

AVERAGE DIESEL RELIABILITY
.950 PRIOR TO MONTH 20;
.800 THEREAFTER

TRIGGER ANALYSES DESIRED
DOUBLE TRIGGER

DETECTION PROBABILITIES DESIRED FOR INTERVALS (IN MONTHS):
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 20 25 30 35 40 45 50 60 75 100

RANDOM NUMBER SEED = -479110

NUMBER OF MONTE CARLO REPLICATIONS = 10000

SIMULATION RESULTS

PROPOSED DOUBLE TRIGGER
MOMENTS
MEAN: 10.73
STD DEV: 7.07
SKEWNESS: .984401
KURTOSIS: 1.14592
QUANTILES
MIN: 1.00
.01: 1.00
.05: 2.00
.10: 3.00
.20: 4.00
.30: 6.00

```
       .40:      8.00
       .50:      9.00
       .60:     11.00
       .70:     14.00
       .80:     16.00
       .90:     20.00
       .95:     24.00
       .99:     32.00
       MAX:     52.00
     DETECTION PROBABILITIES
         1 MONTH:   .05
         2 MONTH:   .10
         3 MONTH:   .15
         4 MONTH:   .20
         5 MONTH:   .26
         6 MONTH:   .32
         7 MONTH:   .38
         8 MONTH:   .44
         9 MONTH:   .50
        10 MONTH:   .56
        11 MONTH:   .61
        12 MONTH:   .66
        13 MONTH:   .70
        14 MONTH:   .74
        15 MONTH:   .78
        20 MONTH:   .90
        25 MONTH:   .96
        30 MONTH:   .99
        35 MONTH:  1.00
        40 MONTH:  1.00
        45 MONTH:  1.00
        50 MONTH:  1.00
        60 MONTH:  1.00
        75 MONTH:  1.00
       100 MONTH:  1.00

  SPRT DOUBLE TRIGGER
     MOMENTS
      MEAN:        10.08
      STD DEV:      7.75
      SKEWNESS:     1.76123
      KURTOSIS:     4.74519
     QUANTILES
       MIN:      1.00
       .01:      1.00
       .05:      2.00
       .10:      2.00
       .20:      4.00
       .30:      5.00
       .40:      6.00
       .50:      8.00
       .60:     10.00
       .70:     12.00
       .80:     15.00
       .90:     20.00
       .95:     25.00
       .99:     37.00
       MAX:     74.00
    DETECTION PROBABILITIES
         1 MONTH:   .04
         2 MONTH:   .11
         3 MONTH:   .14
         4 MONTH:   .22
         5 MONTH:   .32
```

6 MONTH:	.42
7 MONTH:	.49
8 MONTH:	.52
9 MONTH:	.57
10 MONTH:	.64
11 MONTH:	.70
12 MONTH:	.73
13 MONTH:	.75
14 MONTH:	.78
15 MONTH:	.82
20 MONTH:	.91
25 MONTH:	.95
30 MONTH:	.98
35 MONTH:	.99
40 MONTH:	.99
45 MONTH:	1.00
50 MONTH:	1.00
60 MONTH:	1.00
75 MONTH:	1.00
100 MONTH:	1.00

SPRT DOUBLE TRIGGER RECYCLE RESULTS (NO. OF RECYCLES PRIOR TO DETECTION)

MOMENTS

MEAN:	.46
STD DEV:	.66
SKEWNESS:	1.53428
KURTOSIS:	3.05742

QUANTILES

MIN:	.00
.01:	.00
.05:	.00
.10:	.00
.20:	.00
.30:	.00
.40:	.00
.50:	.00
.60:	.00
.70:	1.00
.80:	1.00
.90:	1.00
.95:	2.00
.99:	3.00
MAX:	5.00

TABLE 1

SEQUENTIAL PROBLEM DIESEL TRIGGER

n	D	R	n	D	R	n	D	R
1	†	*	34	6	3	67	10	6
2	2	*	35	6	3	68	10	6
3	2	*	36	6	3	69	10	7
4	3	*	37	6	3	70	10	7
5	3	*	38	6	3	71	10	7
6	3	0	39	6	3	72	10	7
7	3	0	40	7	3	73	10	7
8	3	0	41	7	3	74	10	7
9	3	0	42	7	4	75	10	7
10	3	0	43	7	4	76	10	7
11	3	0	44	7	4	77	11	7
12	3	0	45	7	4	78	11	8
13	4	0	46	7	4	79	11	8
14	4	0	47	7	4	80	11	8
15	4	1	48	7	4	81	11	8
16	4	1	49	8	4	82	11	8
17	4	1	50	8	4	83	11	8
18	4	1	51	8	5	84	11	8
19	4	1	52	8	5	85	11	8
20	4	1	53	8	5	86	12	8
21	4	1	54	8	5	87	12	9
22	5	1	55	8	5	88	12	9
23	5	1	56	8	5	89	12	9
24	5	2	57	8	5	90	12	9
25	5	2	58	9	5	91	12	9
26	5	2	59	9	5	92	12	9
27	5	2	60	9	6	93	12	9
28	5	2	61	9	6	94	12	9
29	5	2	62	9	6	95	13	9
30	5	2	63	9	6	96	13	9
31	6	2	64	9	6	97	13	10
32	6	2	65	9	6	98	13	10
33	6	3	66	9	6	99	13	10
						100	13	10

† Detection requires at least 2 diesel tests in which both tests are failures

* Recycling requires at least 6 diesel tests in which there are no failures

TABLE 2

SEQUENTIAL EARLY WARNING TRIGGER

n	D	R	n	D	R	n	D	R
1	†	*	34	5	3	67	9	6
2	2	*	35	5	3	68	9	6
3	2	*	36	5	3	69	9	6
4	2	*	37	6	3	70	9	7
5	2	*	38	6	3	71	9	7
6	2	*	39	6	3	72	9	7
7	2	0	40	6	3	73	10	7
8	2	0	41	6	3	74	10	7
9	2	0	42	6	3	75	10	7
10	3	0	43	6	4	76	10	7
11	3	0	44	6	4	77	10	7
12	3	0	45	6	4	78	10	7
13	3	0	46	7	4	79	10	8
14	3	0	47	7	4	80	10	8
15	3	0	48	7	4	81	10	8
16	3	1	49	7	4	82	11	8
17	3	1	50	7	4	83	11	8
18	3	1	51	7	4	84	11	8
19	4	1	52	7	5	85	11	8
20	4	1	53	7	5	86	11	8
21	4	1	54	7	5	87	11	8
22	4	1	55	8	5	88	11	8
23	4	1	56	8	5	89	11	9
24	4	1	57	8	5	90	11	9
25	4	2	58	8	5	91	12	9
26	4	2	59	8	5	92	12	9
27	4	2	60	8	5	93	12	9
28	5	2	61	8	6	94	12	9
29	5	2	62	8	6	95	12	9
30	5	2	63	8	6	96	12	9
31	5	2	64	9	6	97	12	9
32	5	2	65	9	6	98	12	10
33	5	2	66	9	6	99	12	10
						100	13	10

† Detection requires at least 2 diesel tests in which both tests are failures
* Recycling requires at least 7 diesel tests in which there are no failures

TABLE 3

SEQUENTIAL DOUBLE TRIGGER (TARGET RELIABILITY = 95%)

n	D	R	n	D	R	n	D	R
1	†	*	34	6	2	67	9	6
2	2	*	35	6	2	68	10	6
3	2	*	36	6	2	69	10	6
4	3	*	37	6	3	70	10	6
5	3	*	38	6	3	71	10	6
6	3	*	39	6	3	72	10	6
7	3	*	40	6	3	73	10	7
8	3	*	41	7	3	74	10	7
9	3	0	42	7	3	75	10	7
10	3	0	43	7	3	76	10	7
11	3	0	44	7	3	77	11	7
12	3	0	45	7	3	78	11	7
13	3	0	46	7	4	79	11	7
14	4	0	47	7	4	80	11	7
15	4	0	48	7	4	81	11	7
16	4	0	49	7	4	82	11	8
17	4	0	50	8	4	83	11	8
18	4	0	51	8	4	84	11	8
19	4	1	52	8	4	85	11	8
20	4	1	53	8	4	86	12	8
21	4	1	54	8	4	87	12	8
22	4	1	55	8	5	88	12	8
23	5	1	56	8	5	89	12	8
24	5	1	57	8	5	90	12	8
25	5	1	58	8	5	91	12	9
26	5	1	59	9	5	92	12	9
27	5	1	60	9	5	93	12	9
28	5	2	61	9	5	94	12	9
29	5	2	62	9	5	95	13	9
30	5	2	63	9	5	96	13	9
31	5	2	64	9	6	97	13	9
32	6	2	65	9	6	98	13	9
33	6	2	66	9	6	99	13	9
						100	13	10

† Detection requires at least 2 diesel tests in which both tests are failures
* Recycling requires at least 9 diesel tests in which there are no failures

TABLE 4

SEQUENTIAL DOUBLE TRIGGER (TARGET RELIABILITY = 97.5%)

n	D	R	n	D	R	n	D	R
1	†	*	34	5	2	67	8	5
2	2	*	35	5	2	68	8	5
3	2	*	36	5	2	69	8	5
4	2	*	37	5	2	70	8	5
5	2	*	38	5	2	71	8	5
6	2	*	39	5	2	72	8	5
7	3	0	40	5	2	73	8	5
8	3	0	41	6	3	74	8	5
9	3	0	42	6	3	75	8	5
10	3	0	43	6	3	76	9	6
11	3	0	44	6	3	77	9	6
12	3	0	45	6	3	78	9	6
13	3	0	46	6	3	79	9	6
14	3	0	47	6	3	80	9	6
15	3	0	48	6	3	81	9	6
16	3	0	49	6	3	82	9	6
17	3	0	50	6	3	83	9	6
18	4	1	51	6	3	84	9	6
19	4	1	52	6	3	85	9	6
20	4	1	53	7	4	86	9	6
21	4	1	54	7	4	87	10	7
22	4	1	55	7	4	88	10	7
23	4	1	56	7	4	89	10	7
24	4	1	57	7	4	90	10	7
25	4	1	58	7	4	91	10	7
26	4	1	59	7	4	92	10	7
27	4	1	60	7	4	93	10	7
28	4	1	61	7	4	94	10	7
29	4	1	62	7	4	95	10	7
30	5	2	63	7	4	96	10	7
31	5	2	64	8	5	97	10	7
32	5	2	65	8	5	98	10	7
33	5	2	66	8	5	99	11	8
						100	11	8

† Detection requires at least 2 diesel tests in which both tests are failures
* Recycling requires at least 7 diesel tests in which there are no failures

Figure 1

Comparative Performance Of Both SAIC and LANL For Detecting A Single-Diesel Degradation To Reliability R

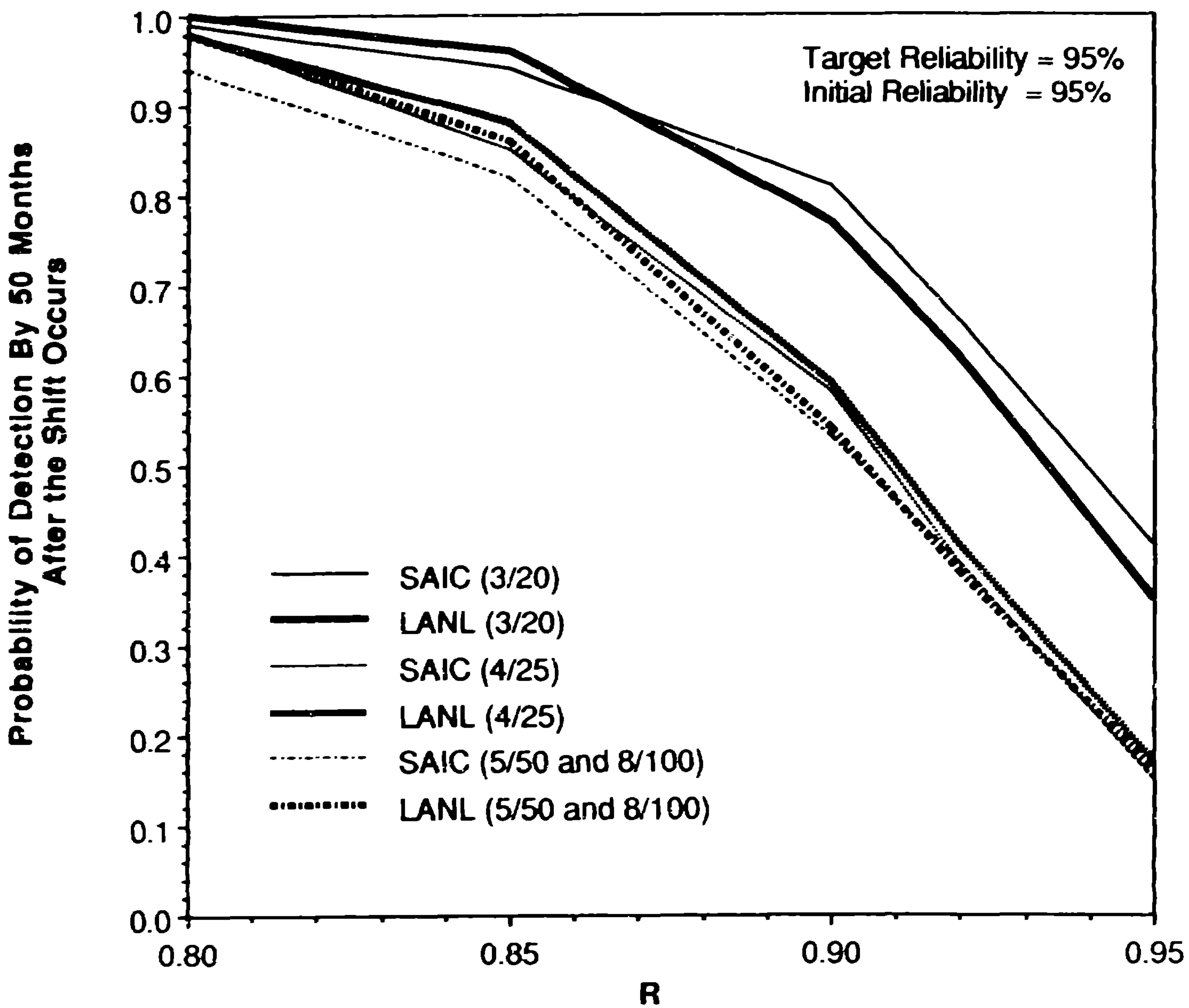


Figure 2

The Effect Of Initial Reliability RI On The Performance Of The Proposed Double (5/50 and 8/100) Trigger For Detecting A Two-Diesel Degradation To Reliability R = 90%

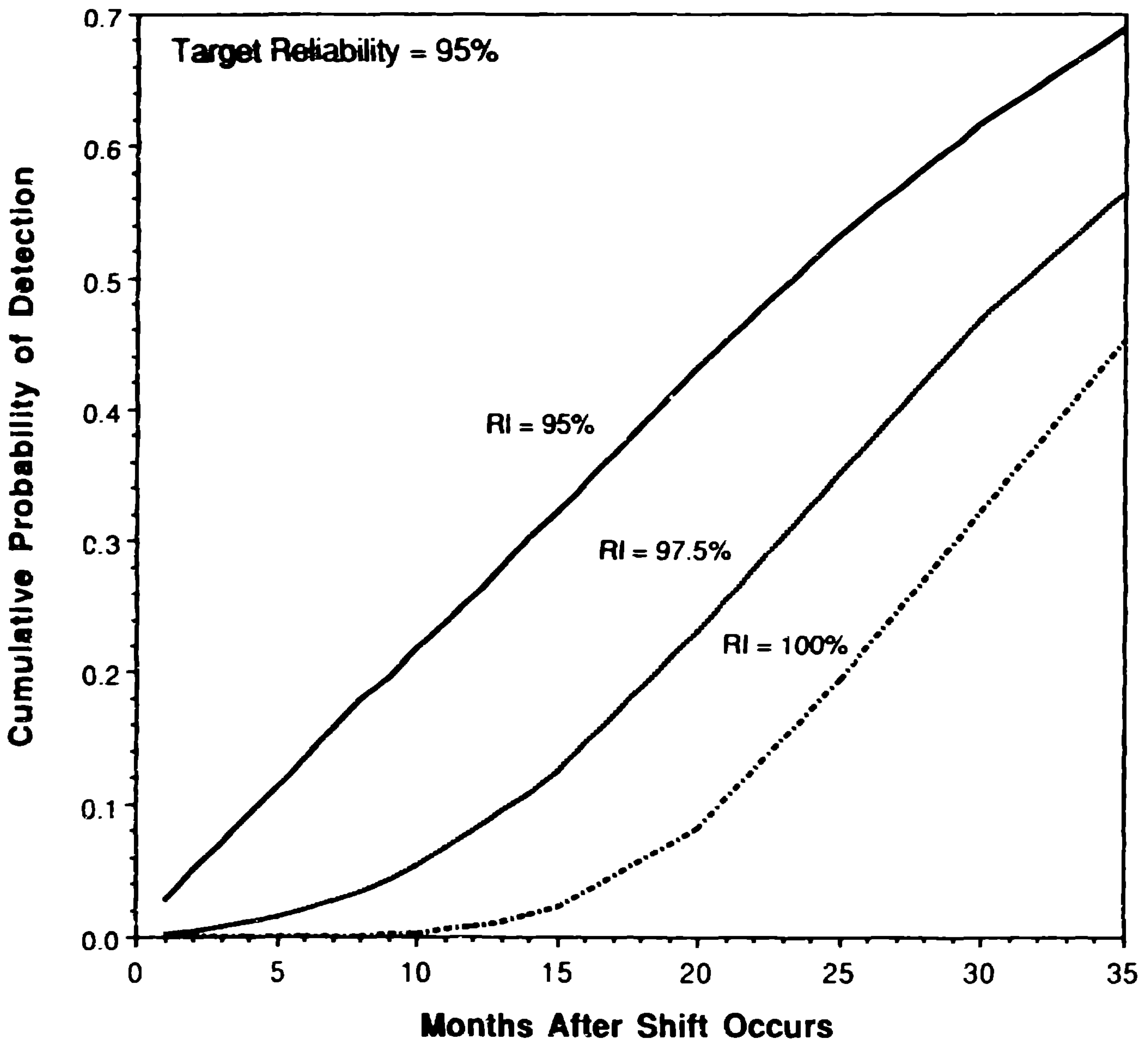
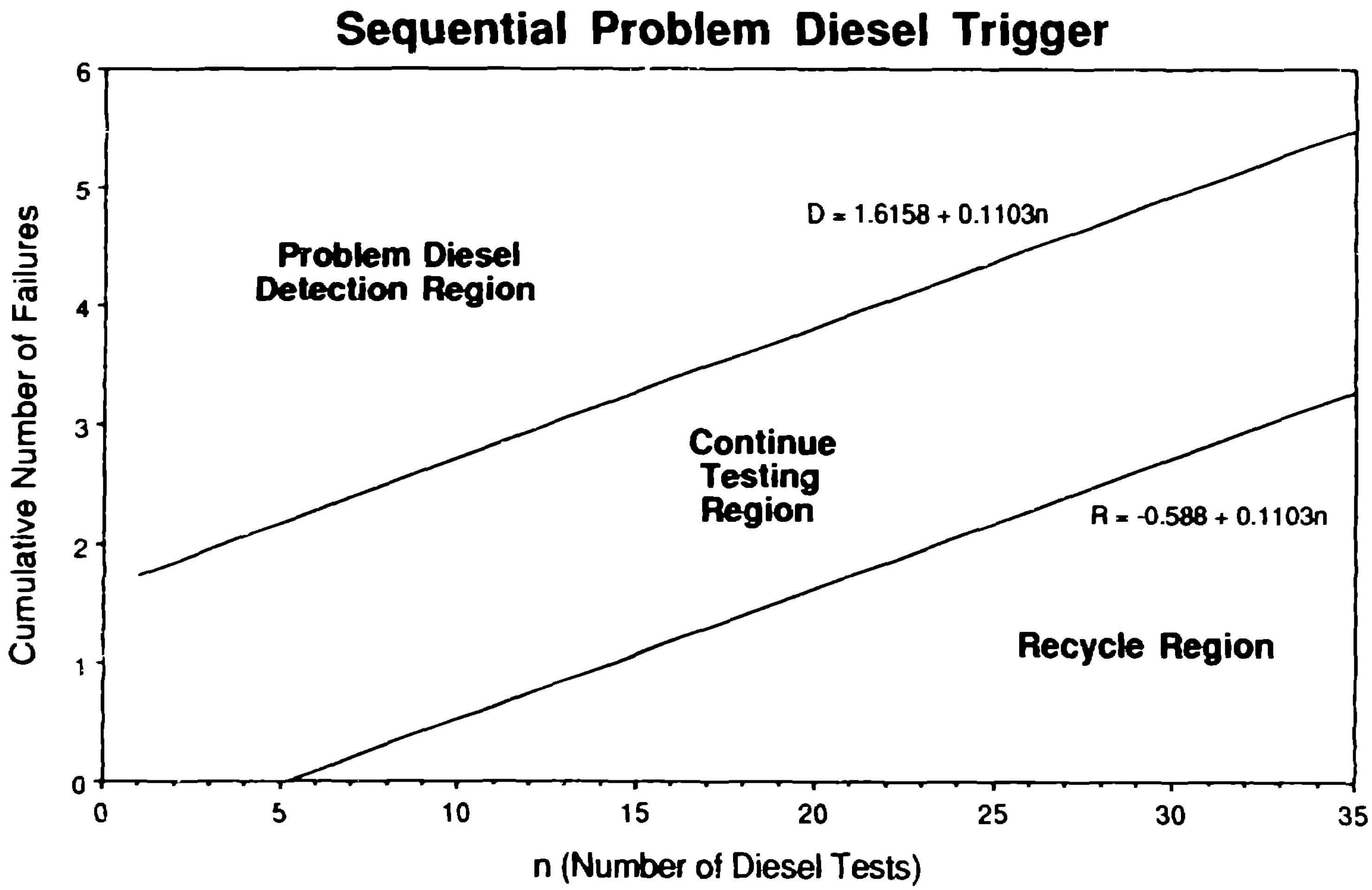


Figure 3



Sequential Problem Diesel Trigger
6
5
4
3
2
1
0
0
5
10
15
20
25
30
35
Cumulative Number of Failures
n (Number of Diesel Tests)
D = 1.6158 + 0.1103n
R = -0.588 + 0.1103n
Problem Diesel Detection Region
Continue Testing Region
Recycle Region

The Effect Of Initial Reliability On The Performance Of The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20

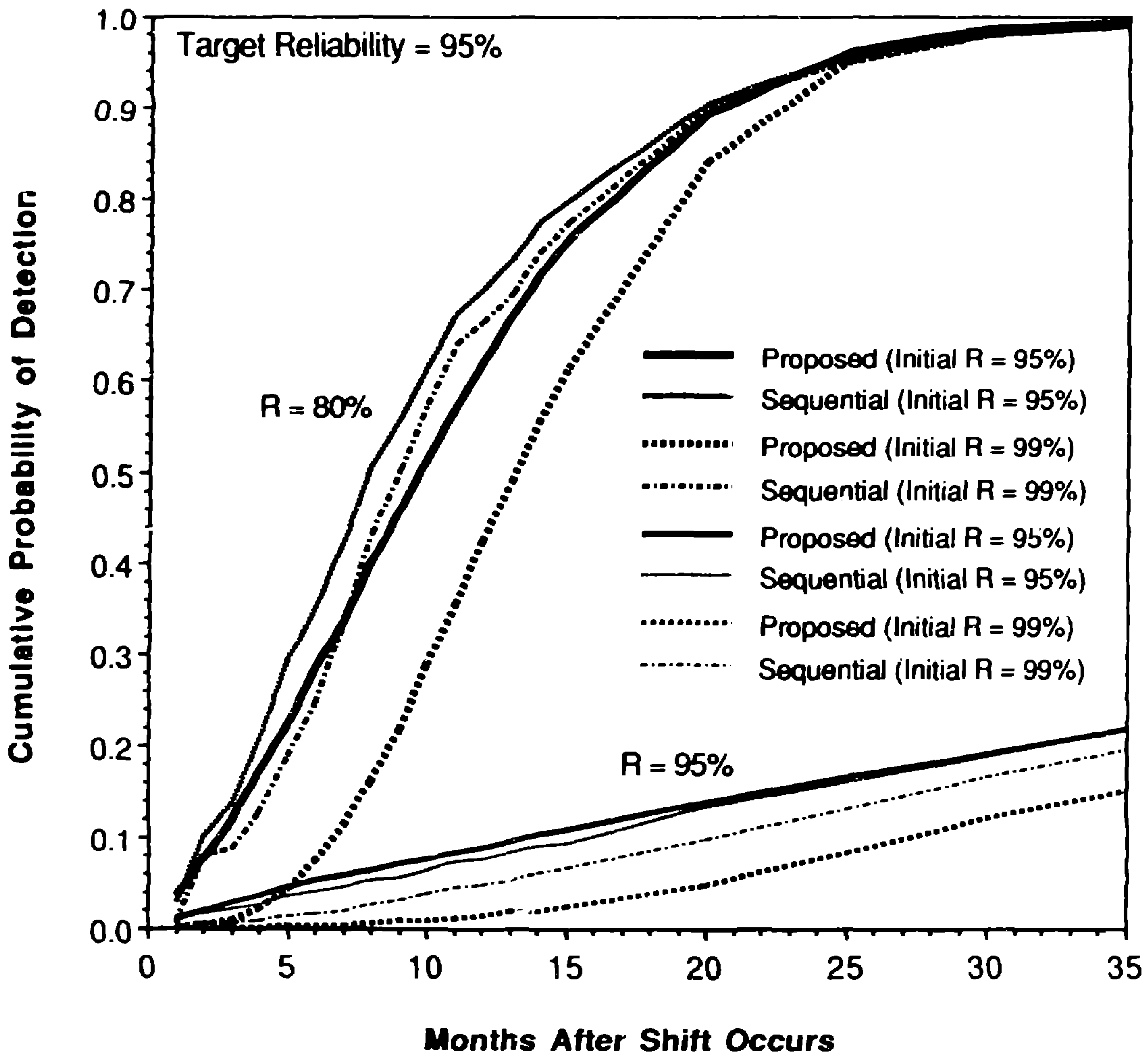


Figure 5

Performance Of The Wald Sequential Trigger In Detecting a Two-Diesel Shift To Reliability R As A Function Of The Month In Which The Shift Occurs

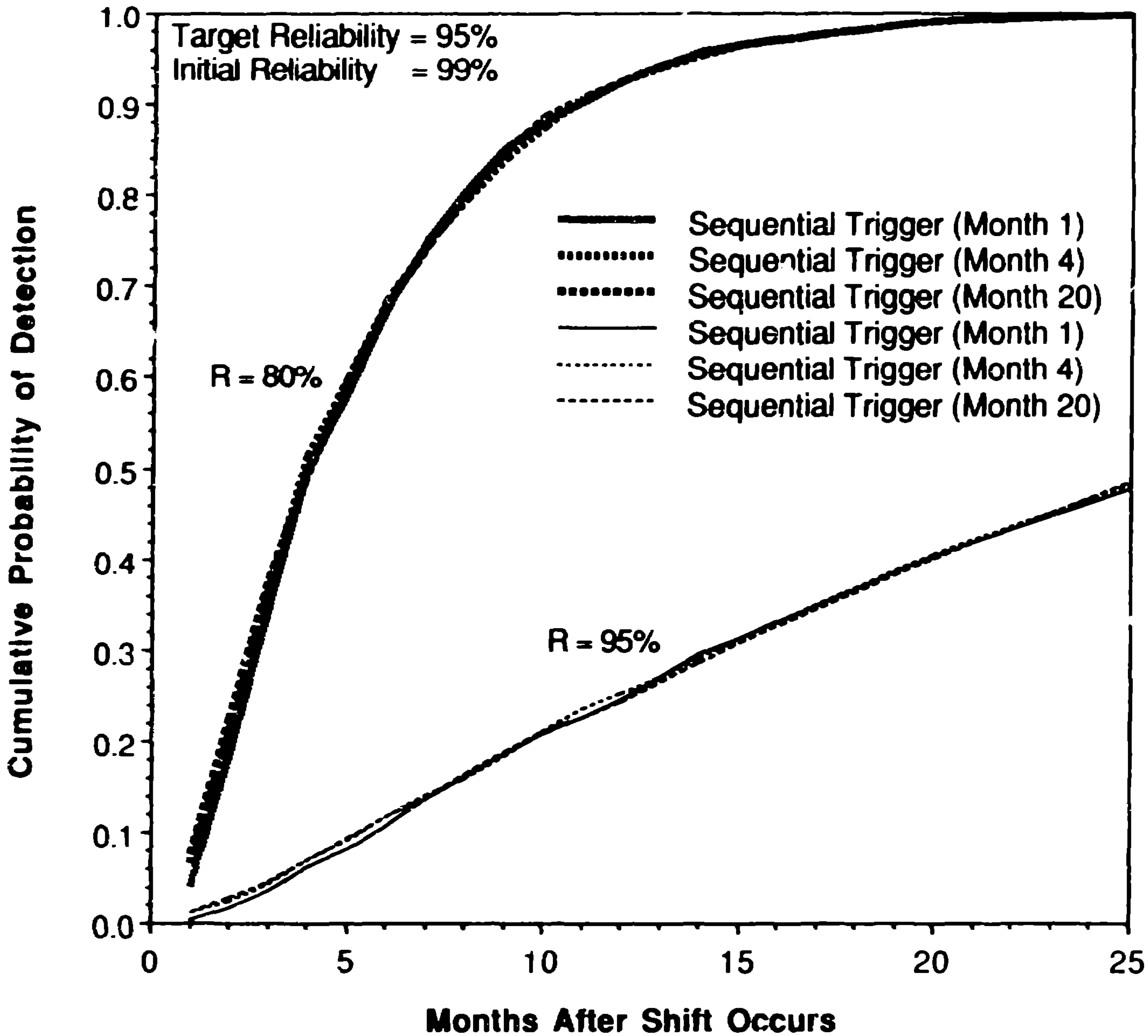
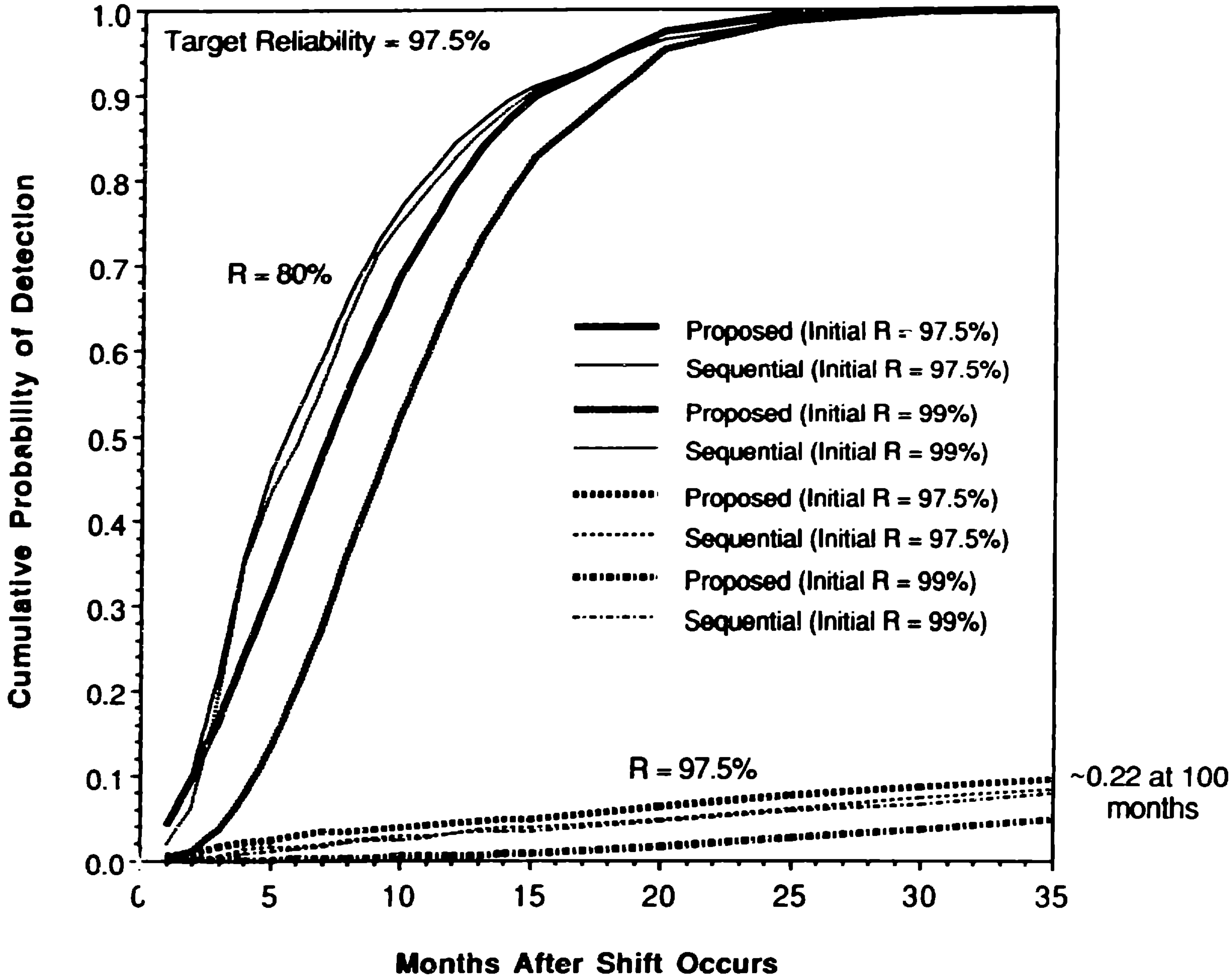


Figure 6

The Effect Of Initial Reliability On The Performance Of The Proposed Double (4/50 and 5/100) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20



Comparative Performance Of Both The Proposed Double (4/50 and 5/100) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 97.5%)

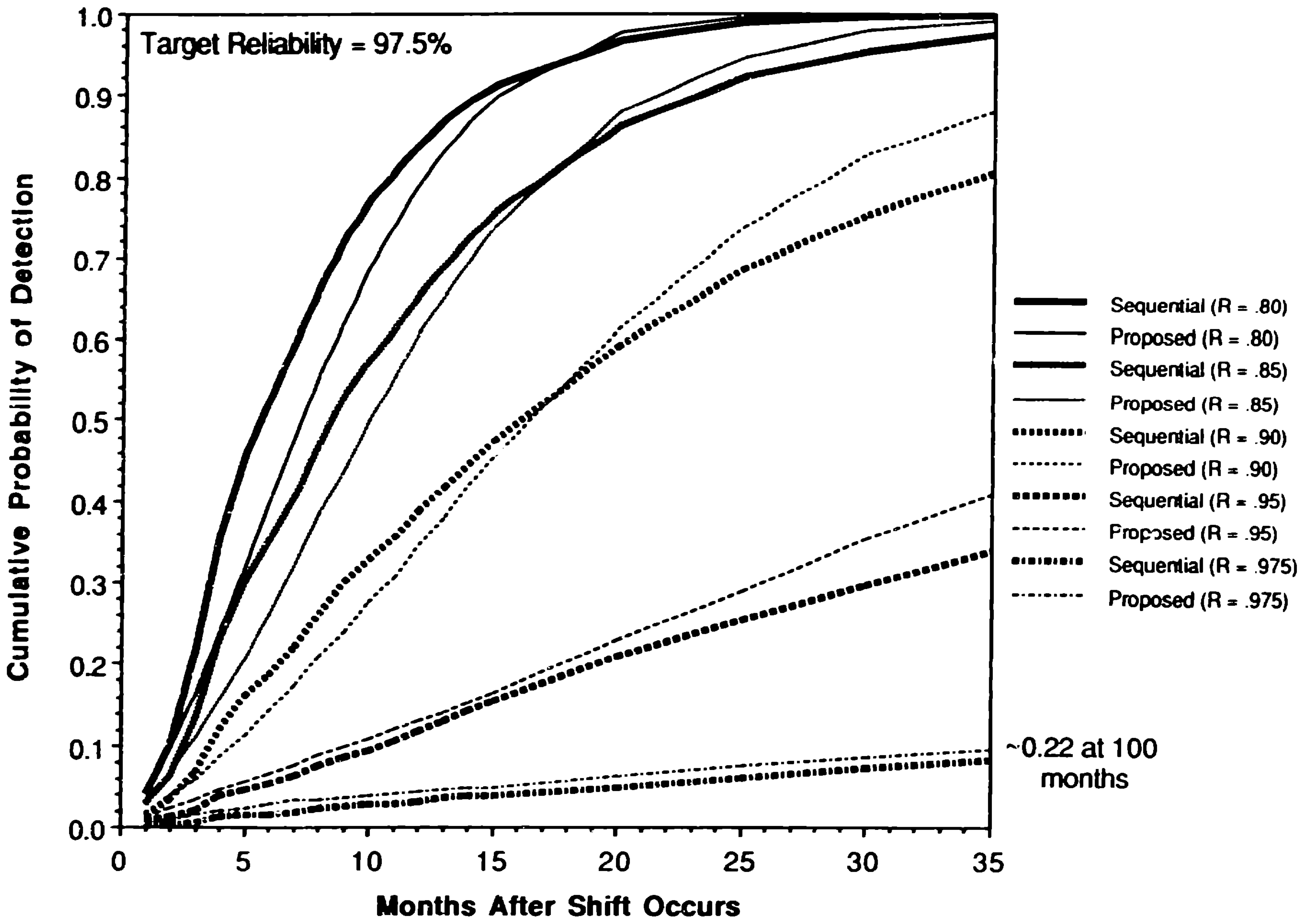
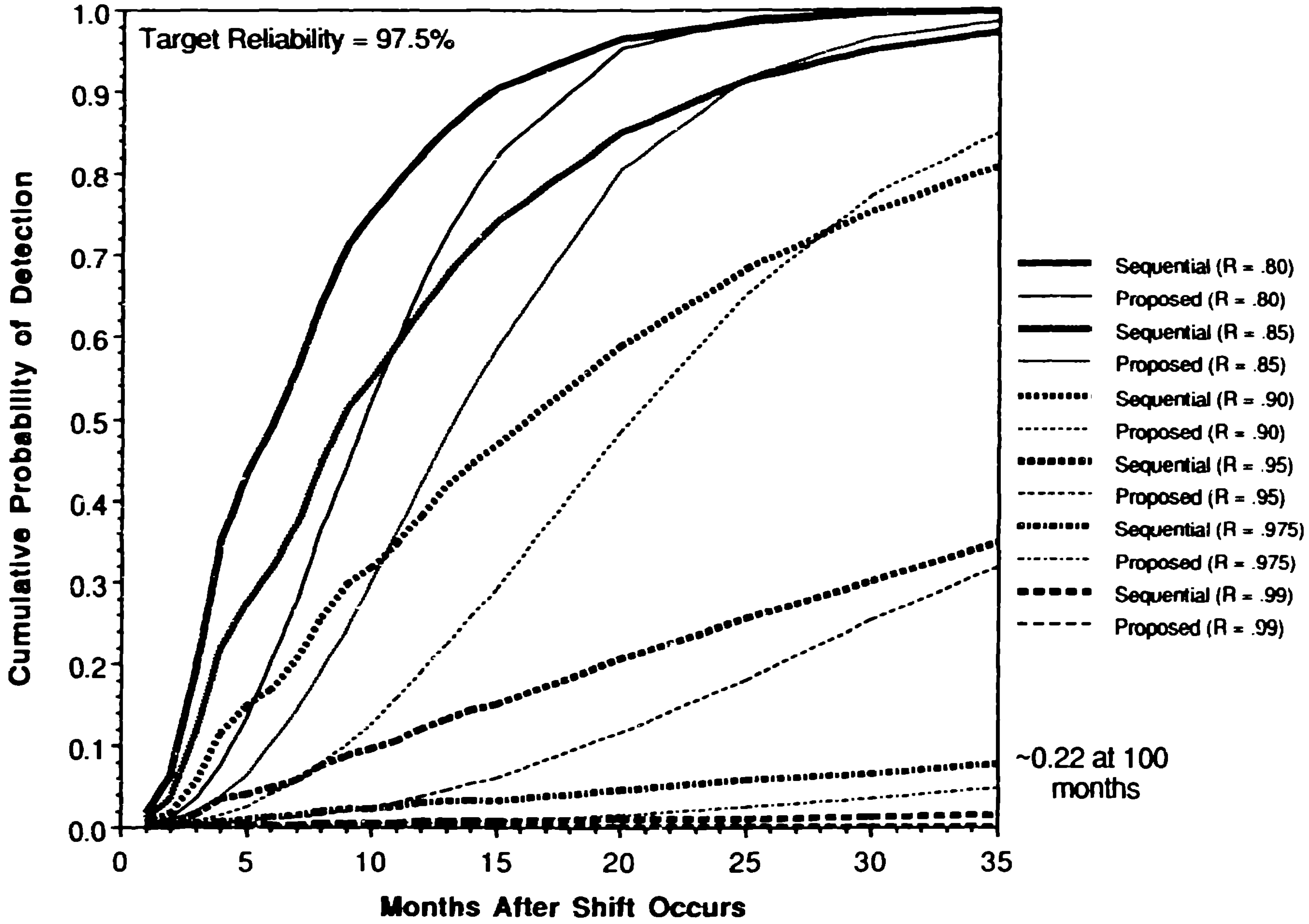
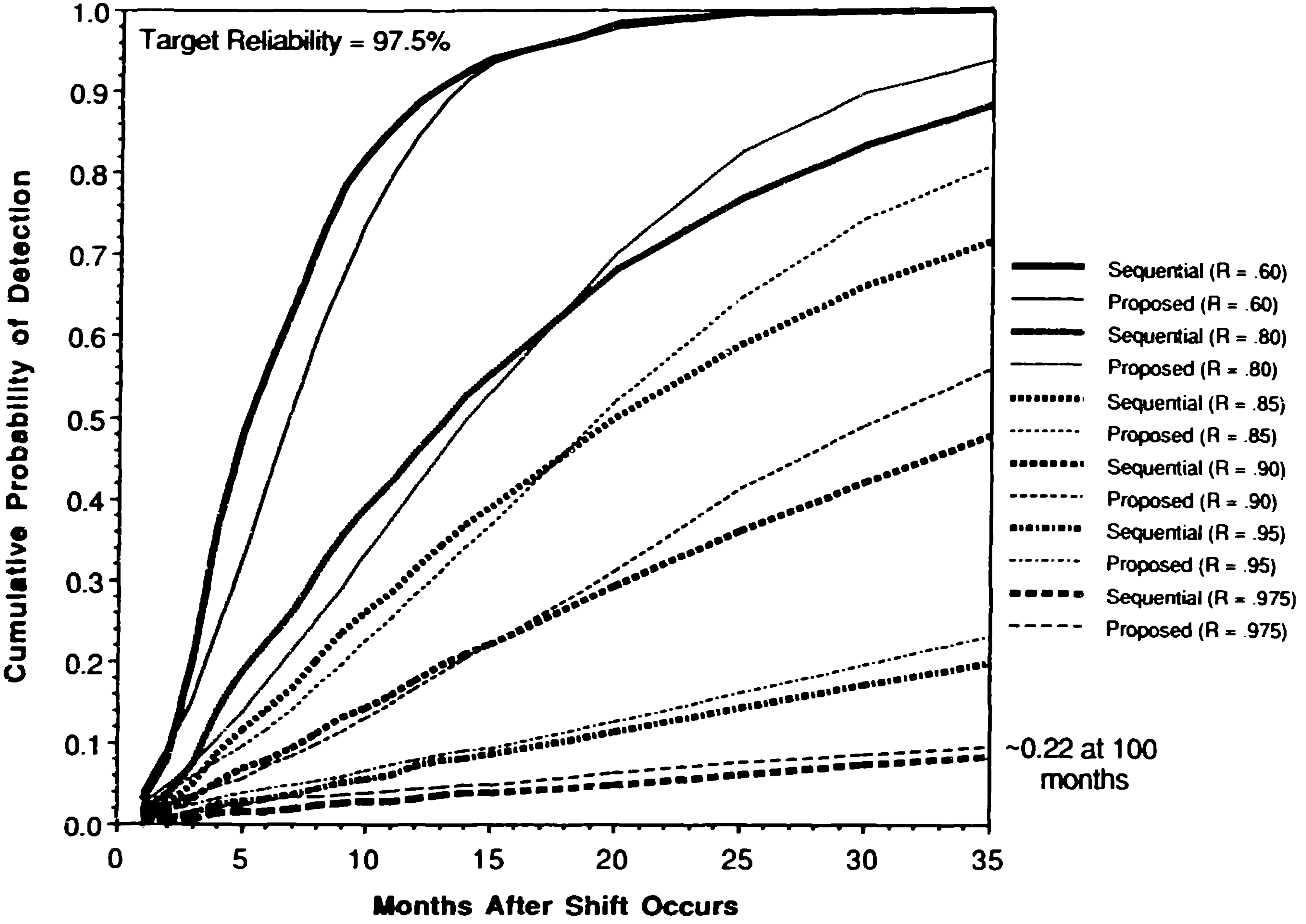


Figure 8

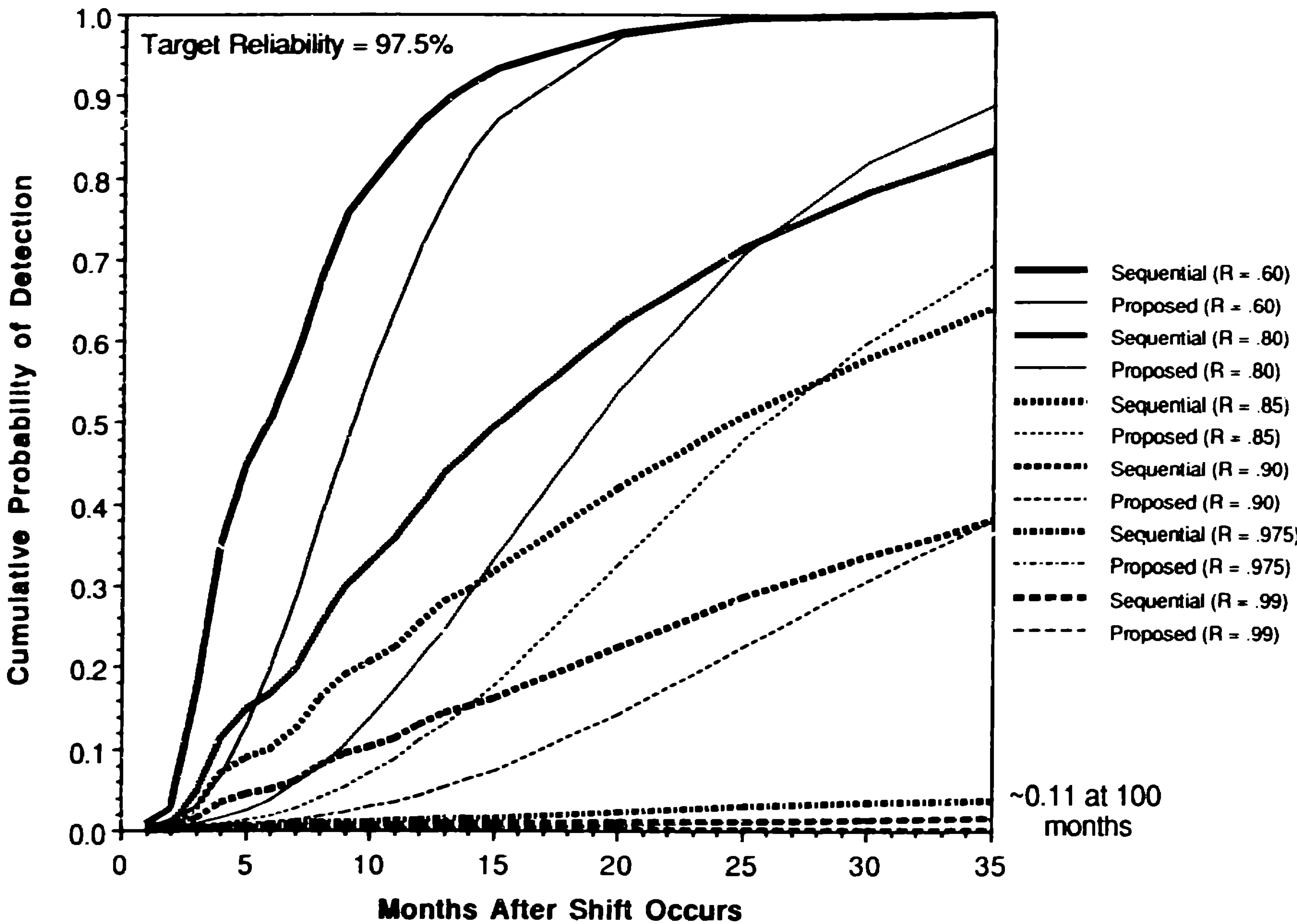
Comparative Performance Of Both The Proposed Double (4/50 and 5/100) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)



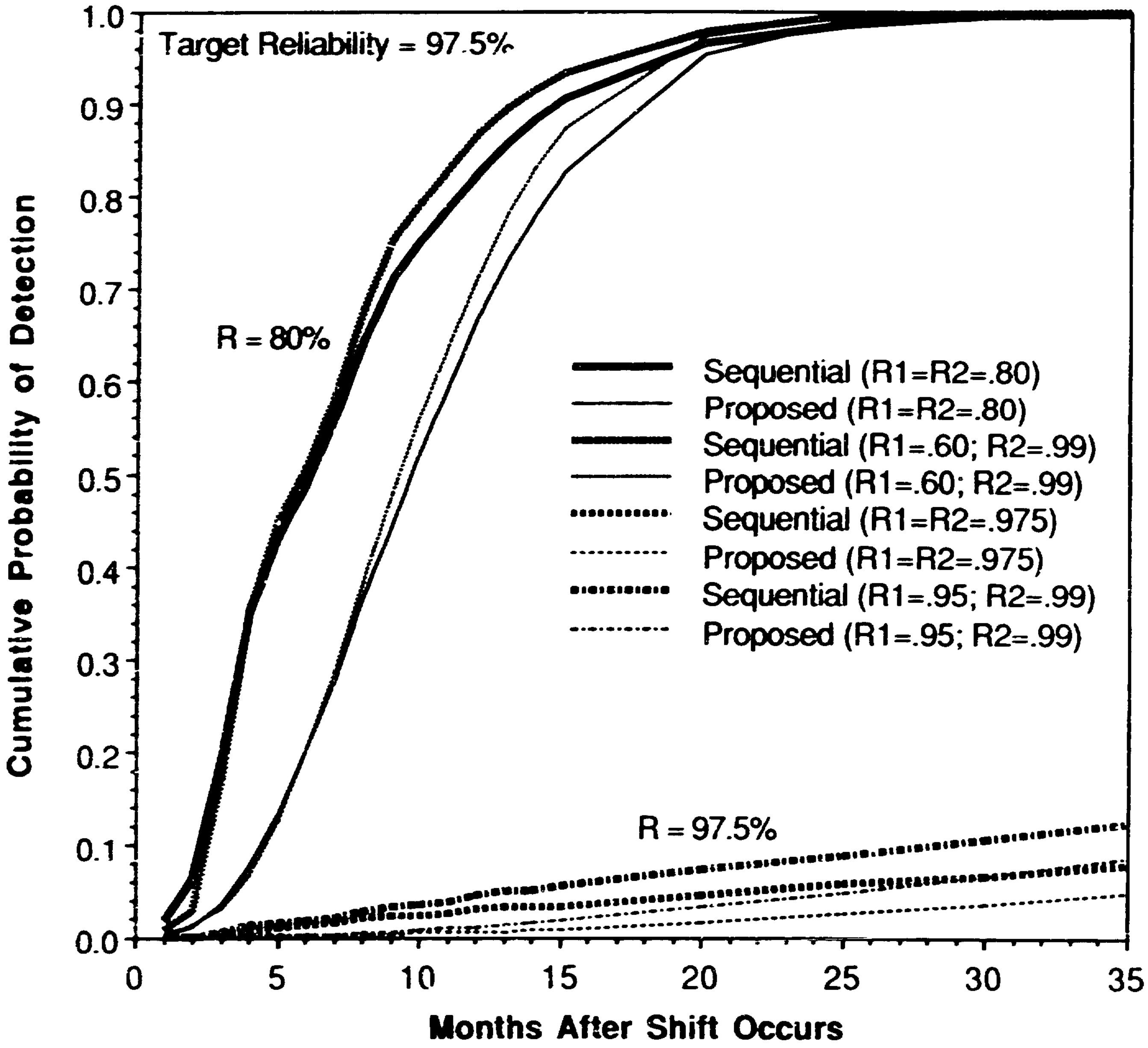
Comparative Performance Of Both The Proposed Double (4/50 and 5/100) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 97.5%)



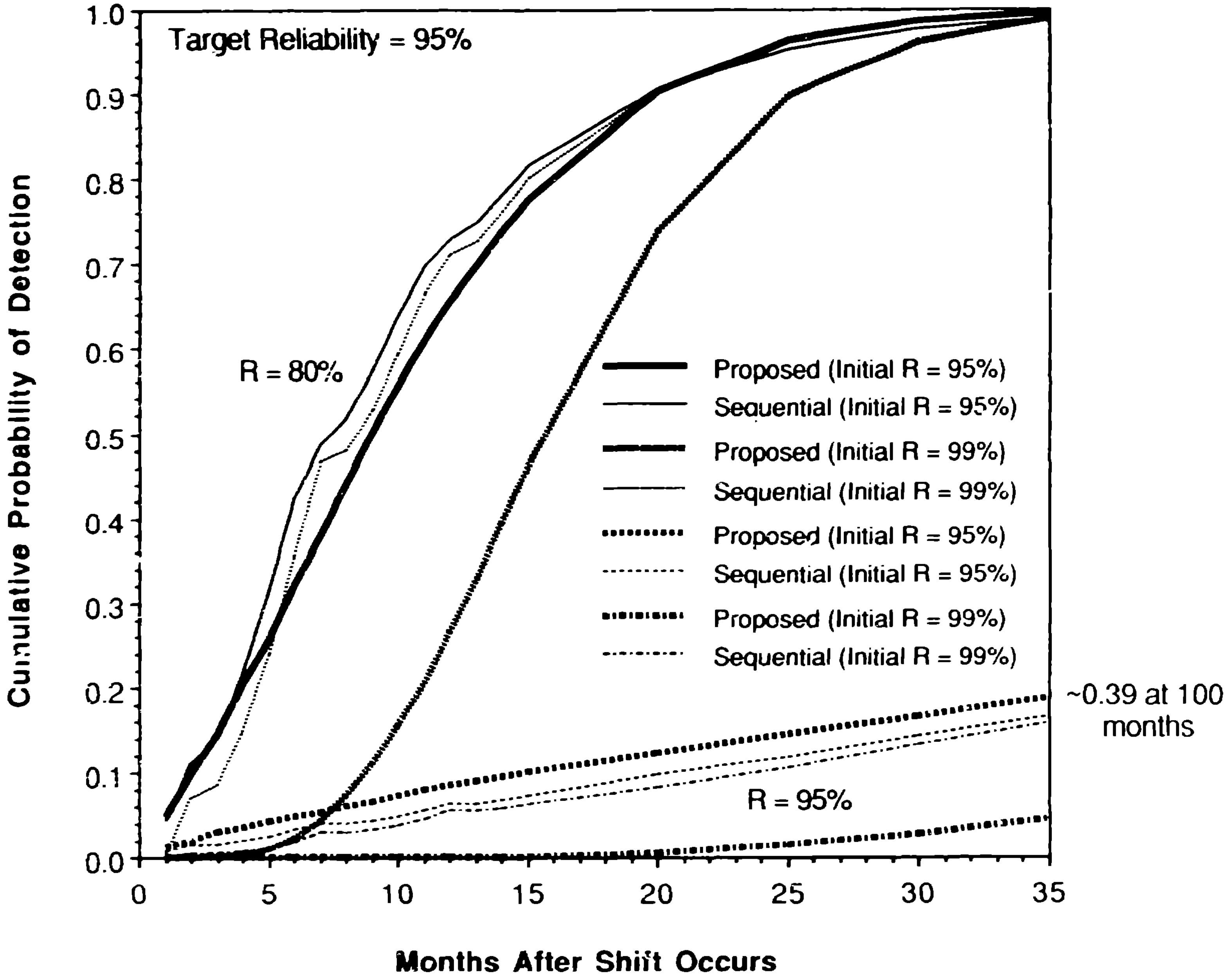
Comparative Performance Of Both The Proposed Double (4/50 and 5/100) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)



Comparative Performance Of Both The Proposed Double (4/50 and 5/100) and Wald Sequential Triggers For Detecting A Shift To Average Reliability R At Month 20 (Initial Reliability = 99%)



The Effect Of Initial Reliability On The Performance Of The Proposed Double (5/50 and 8/100) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20



Comparative Performance Of Both The Proposed Double (5/50 and 8/100) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 95%)

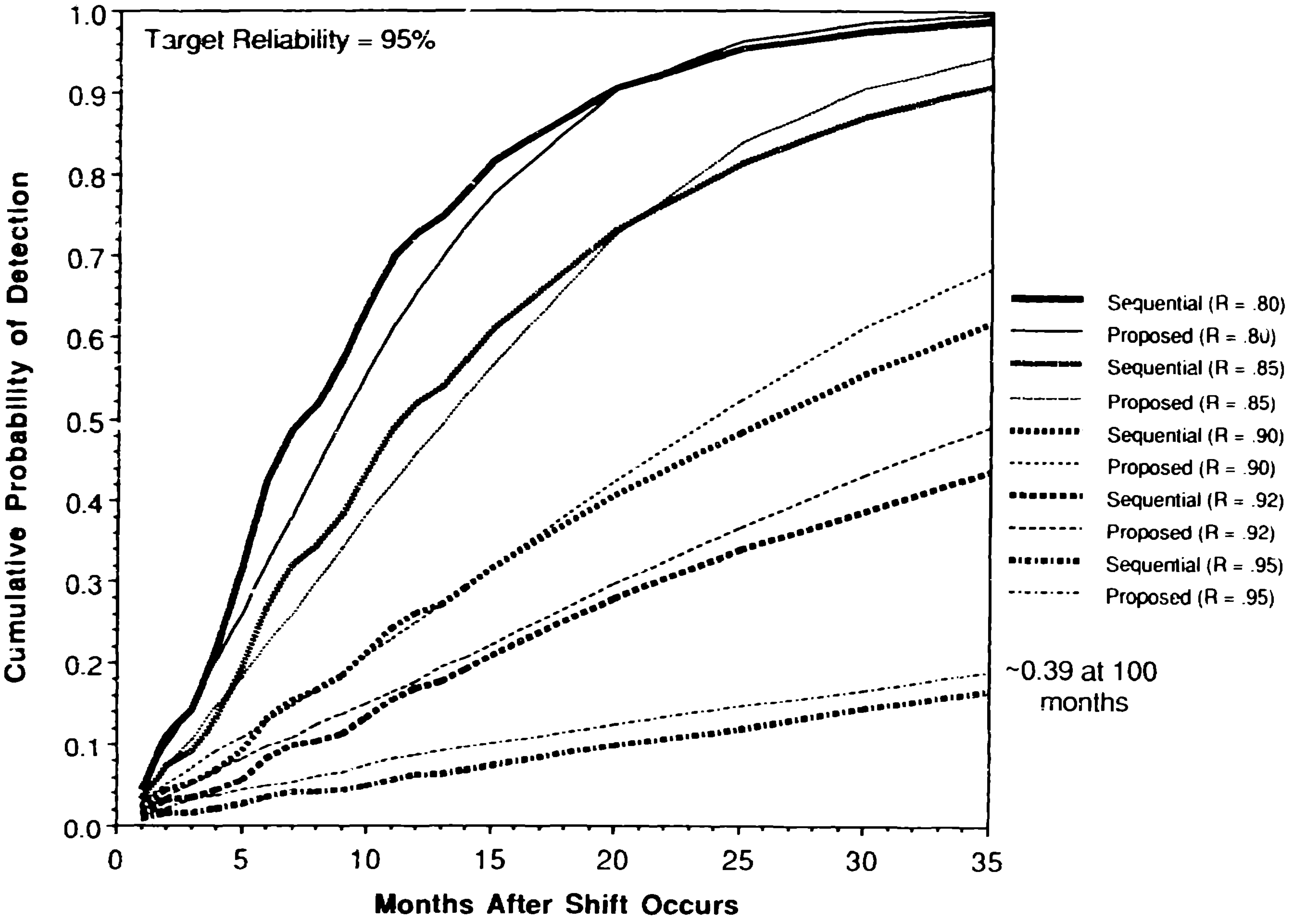


Figure 14

Comparative Performance Of Both The Proposed Double (5/50 and 8/100) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)

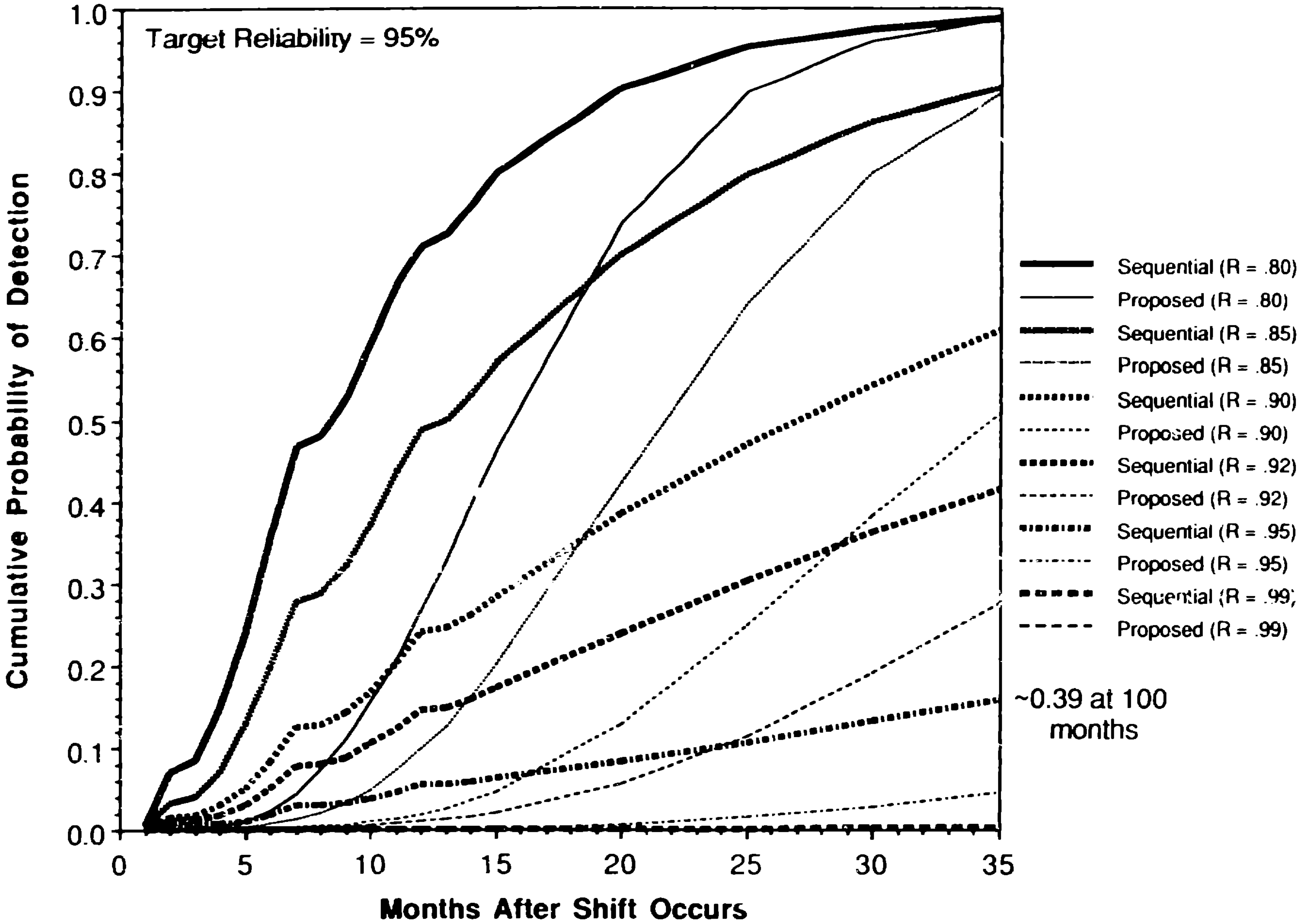


Figure 13

Comparative Performance Of Both The Proposed Double (5/50 and 8/100) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 95%)

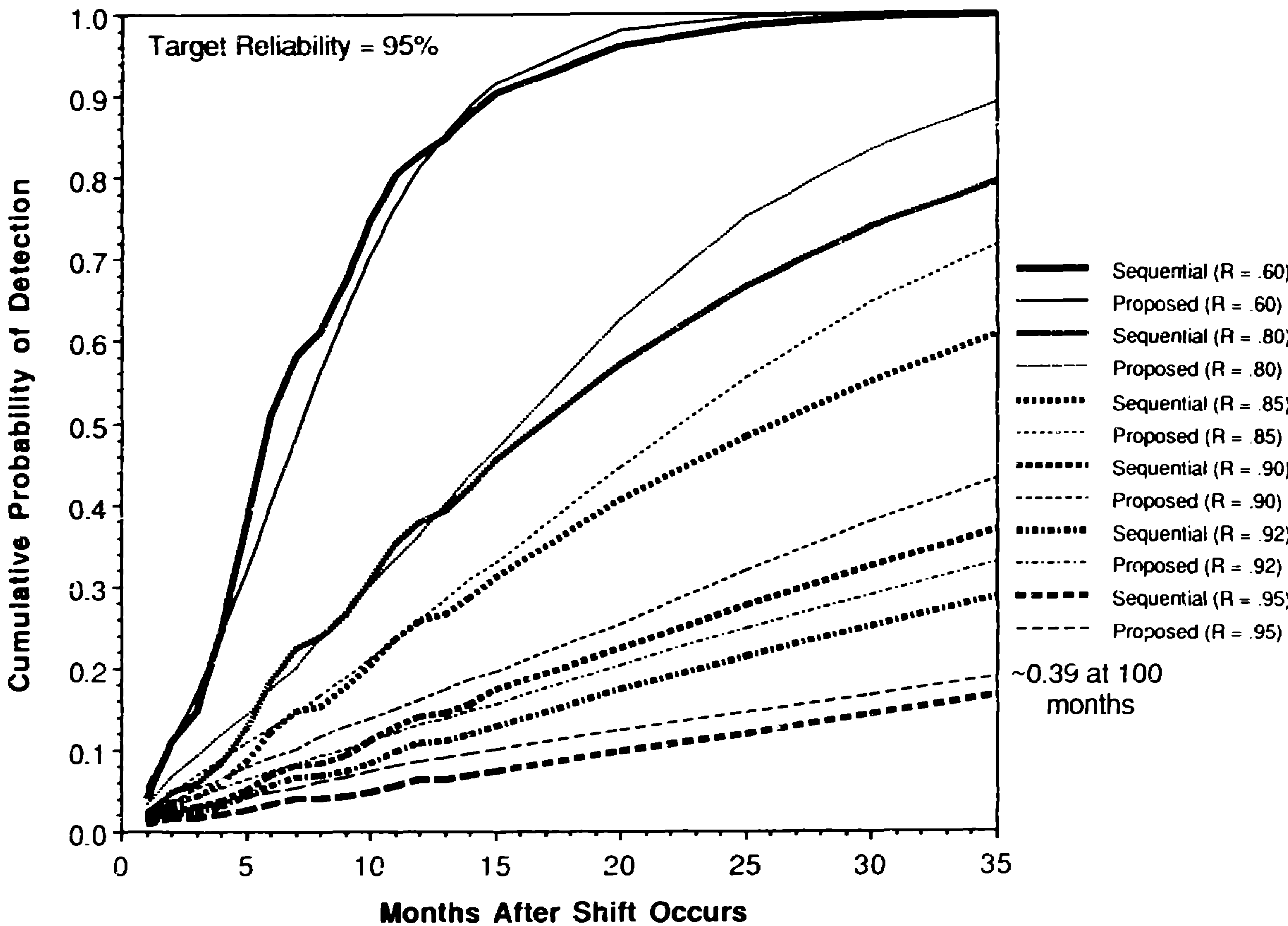
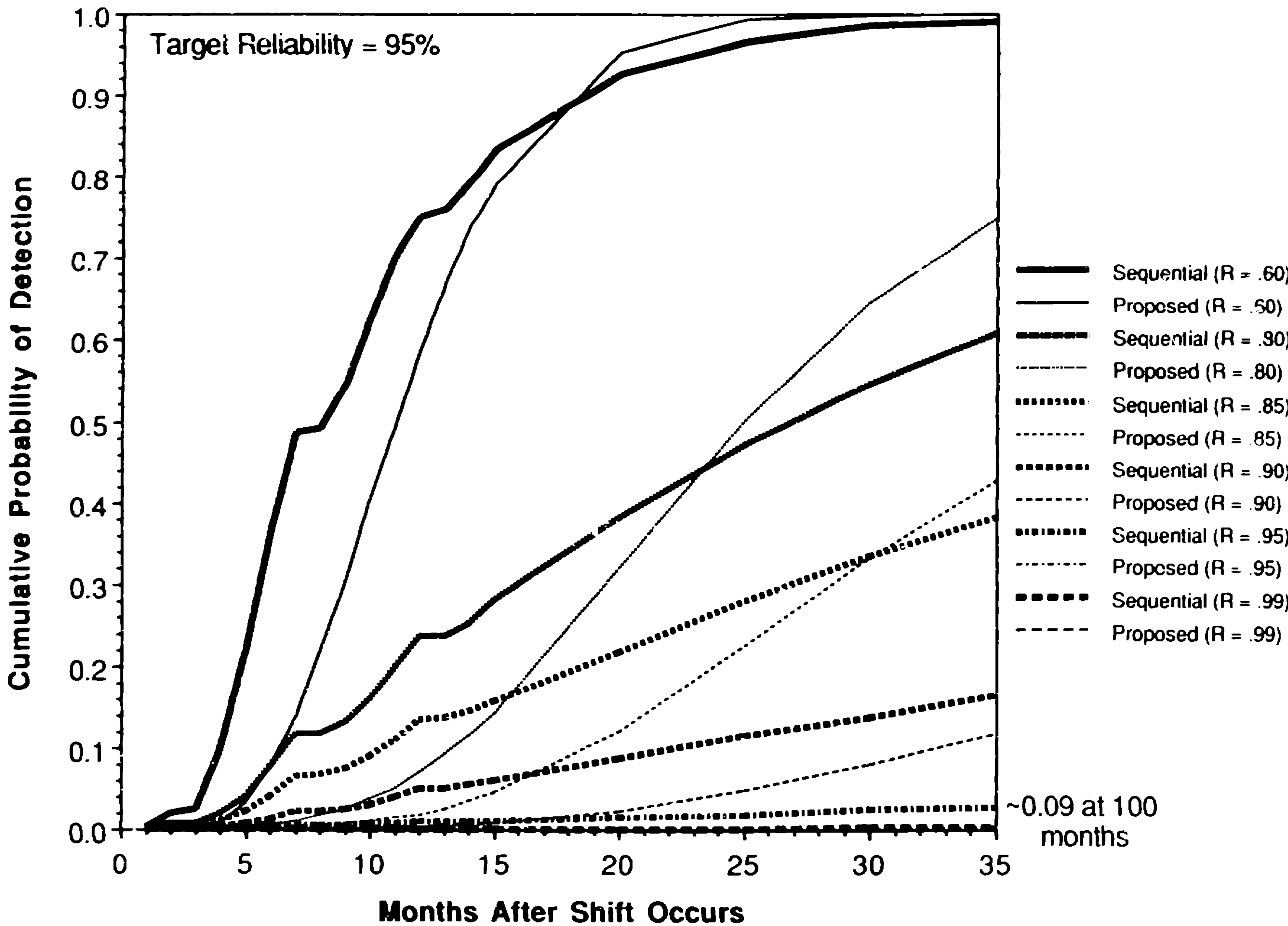
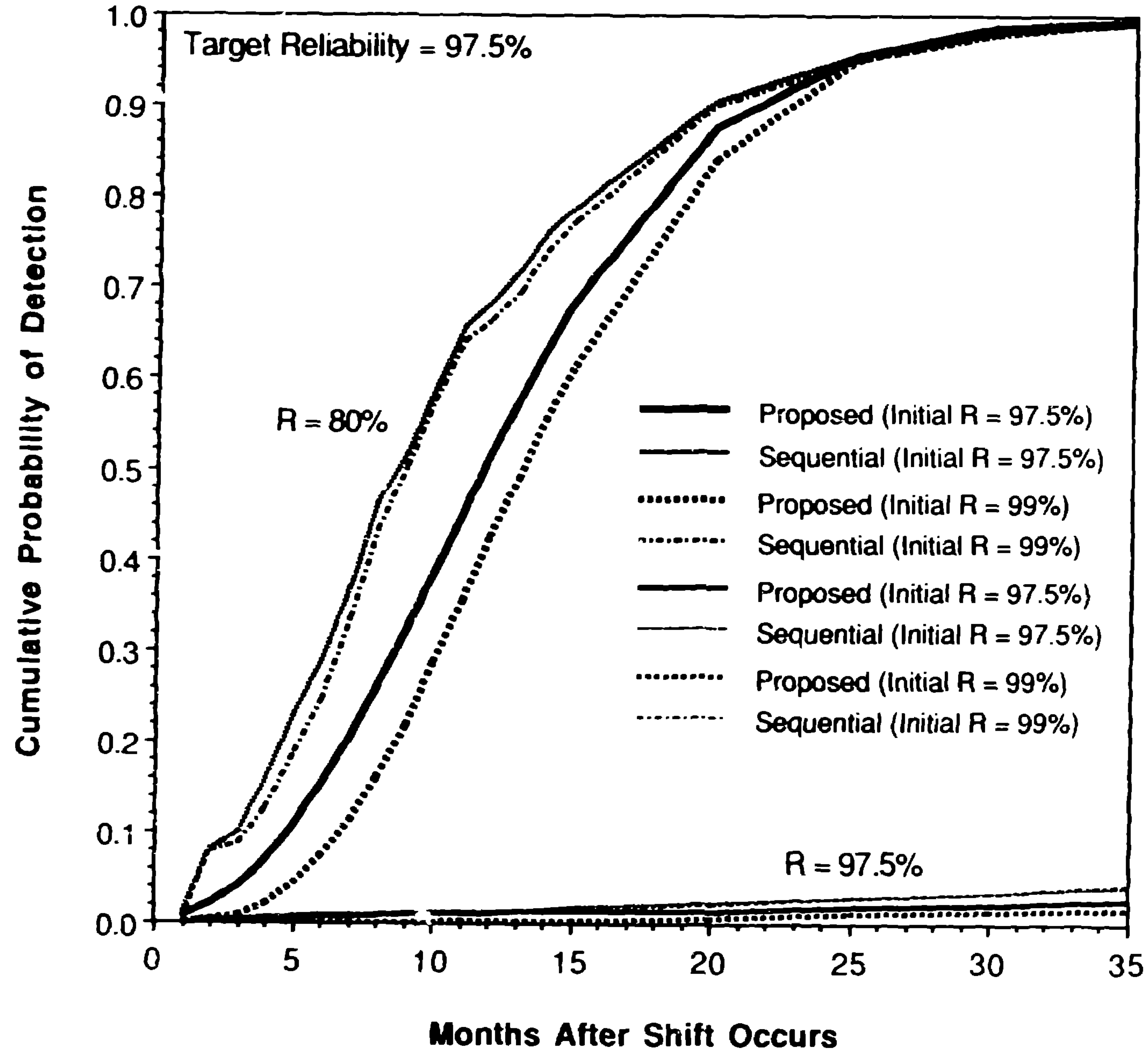


Figure 16

Comparative Performance Of Both The Proposed Double (5/50 and 8/100) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)



The Effect Of Initial Reliability On The Performance Of The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20



Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 95%)

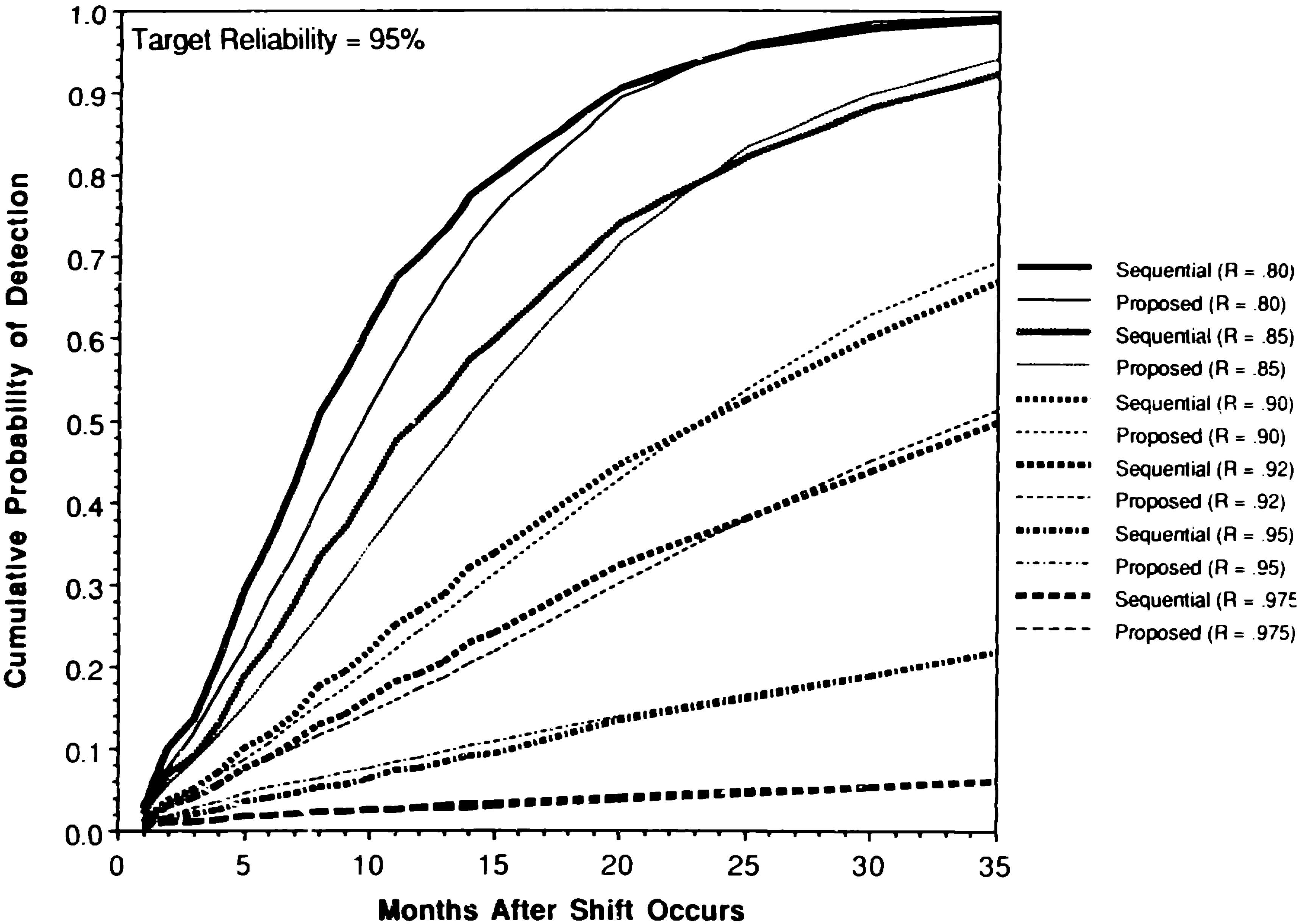


Figure 19

Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 97.5%)

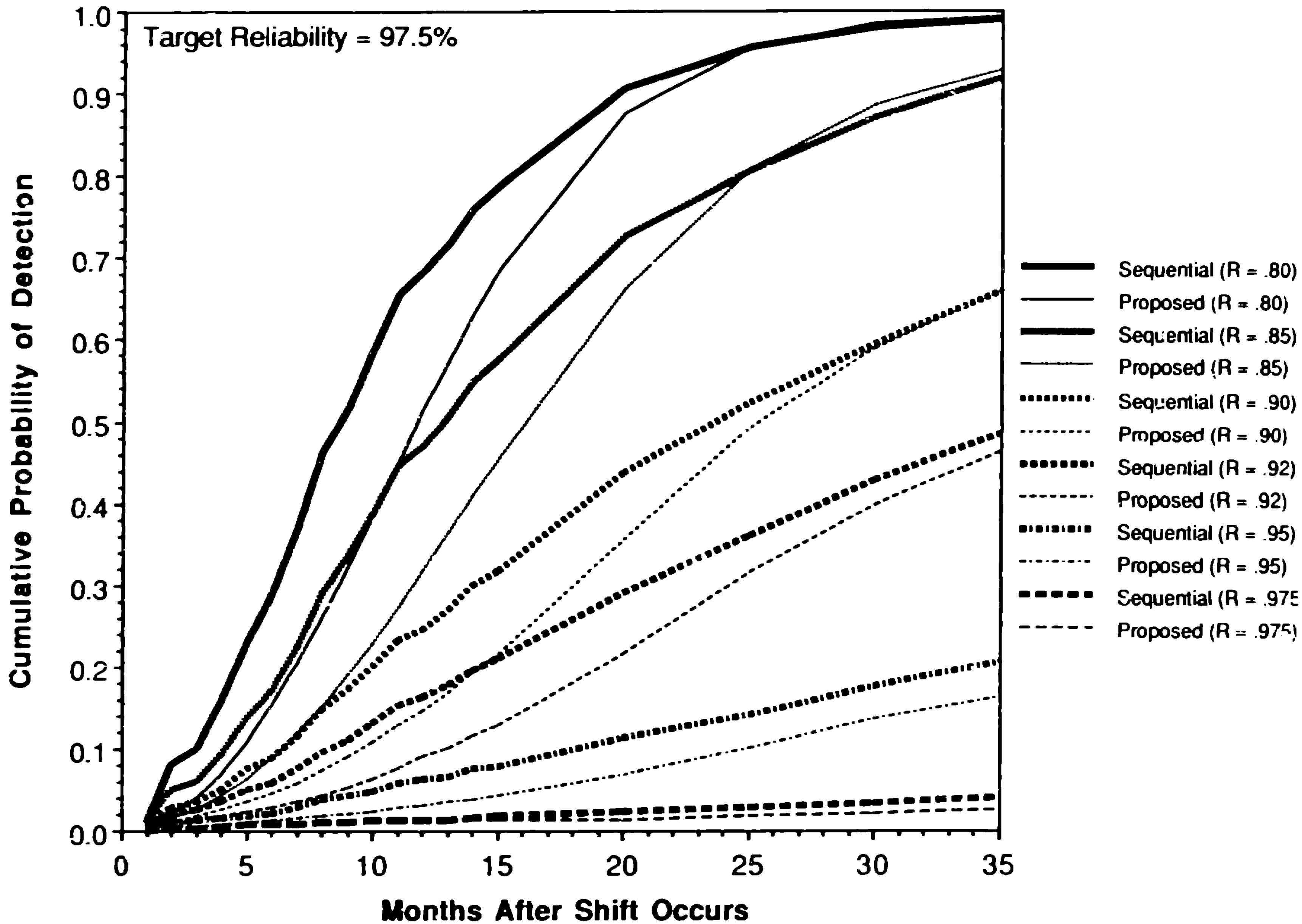
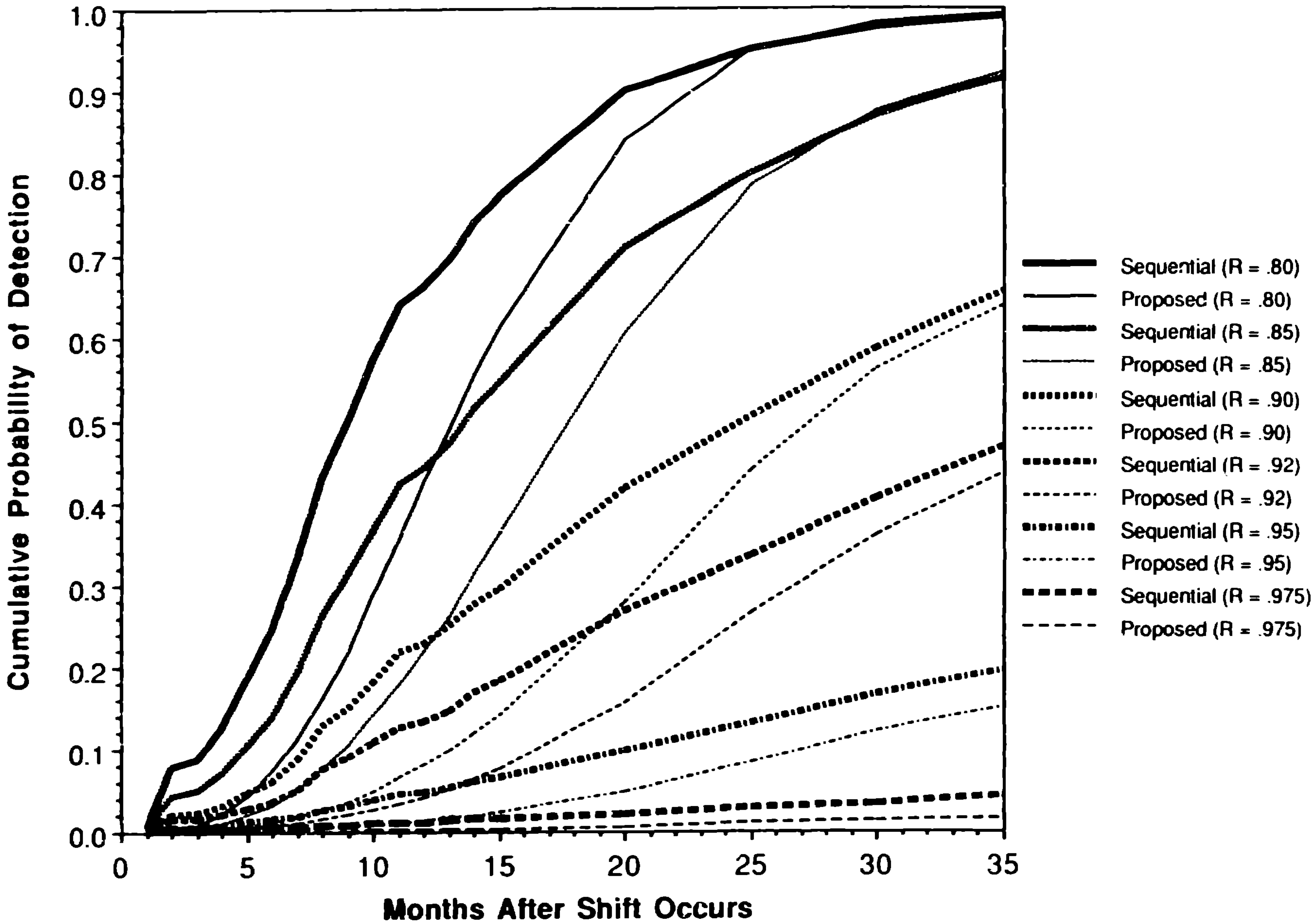


Figure 20

Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)



Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 95%)

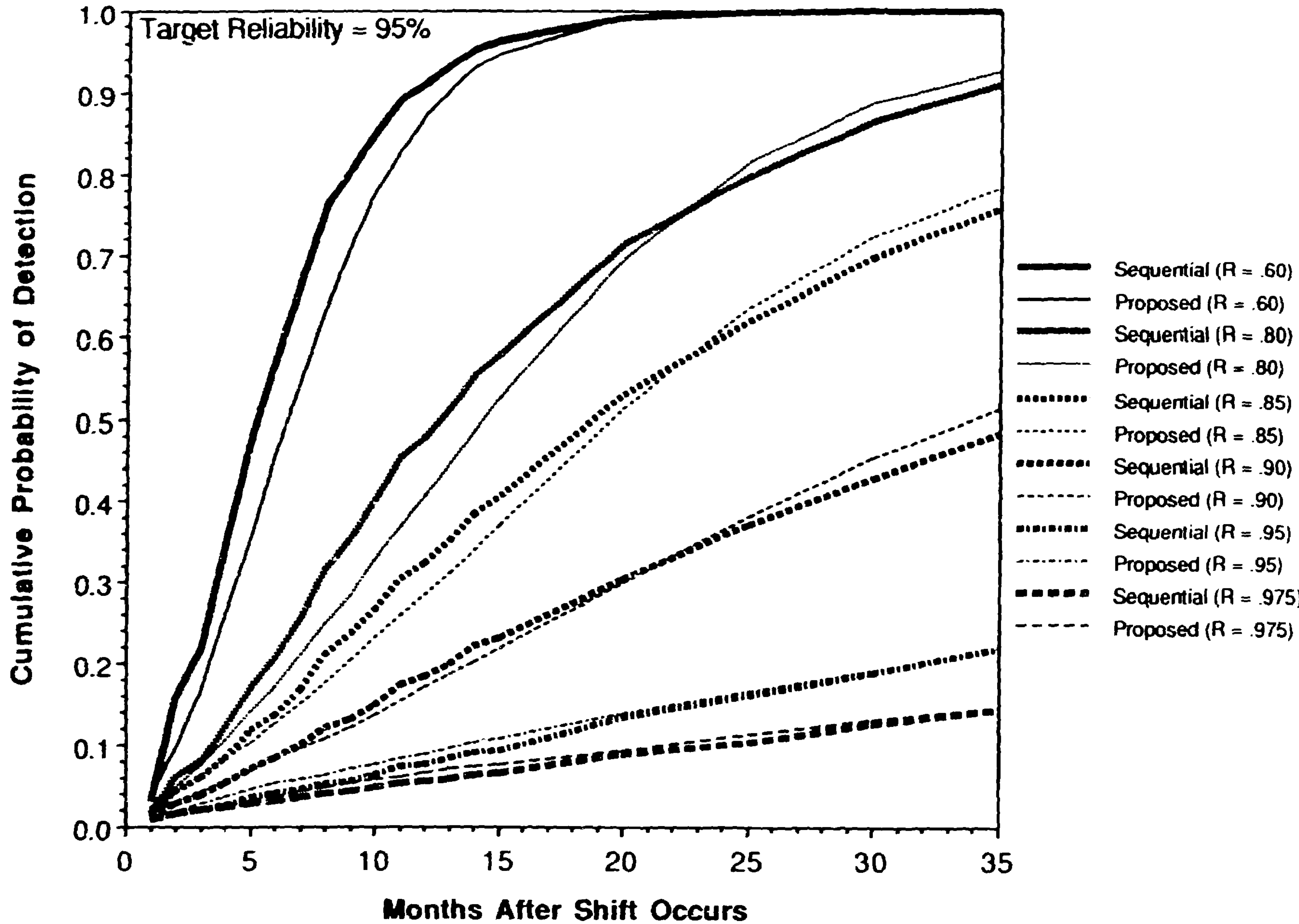
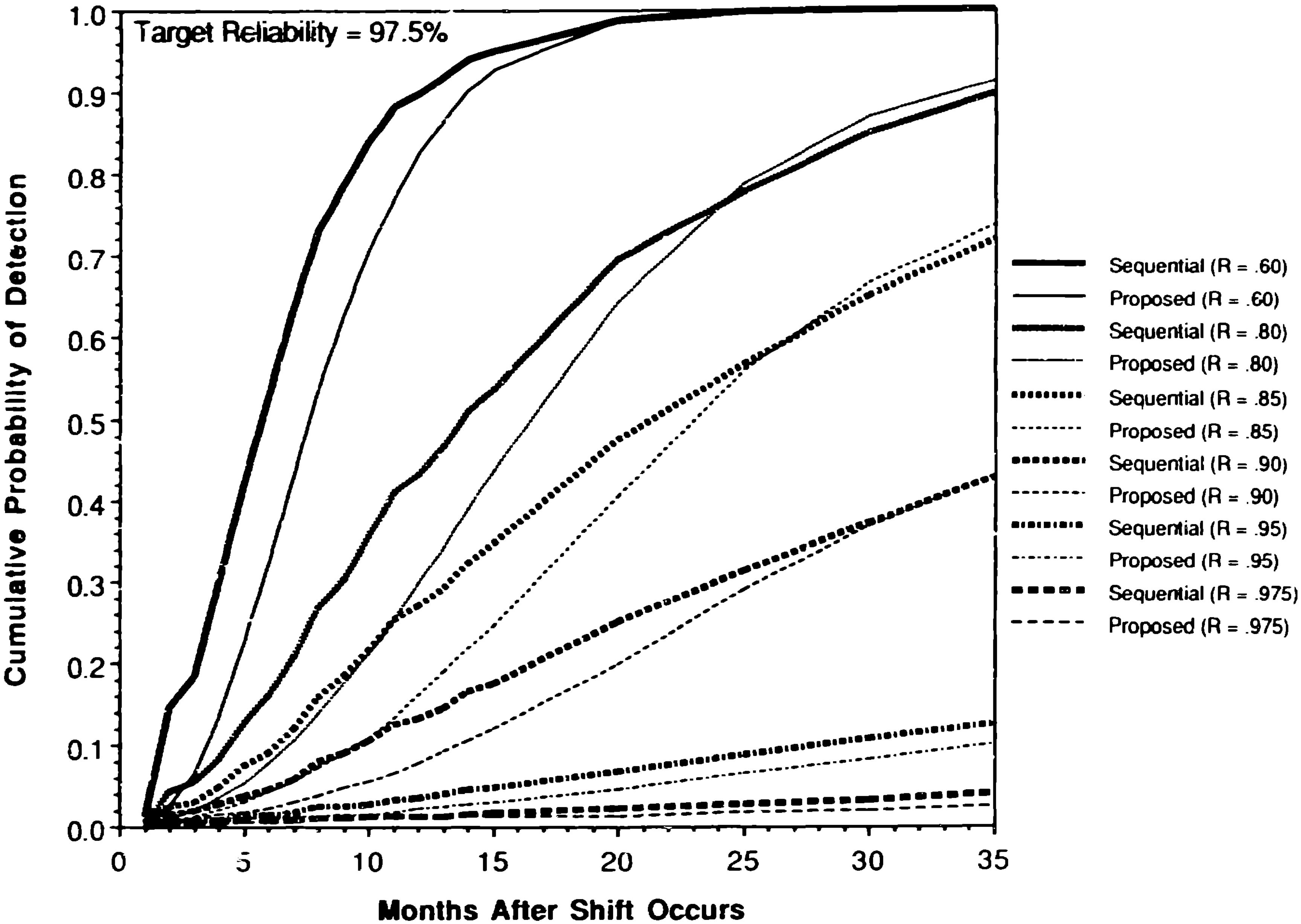


Figure 22

Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 97.5%)



Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)

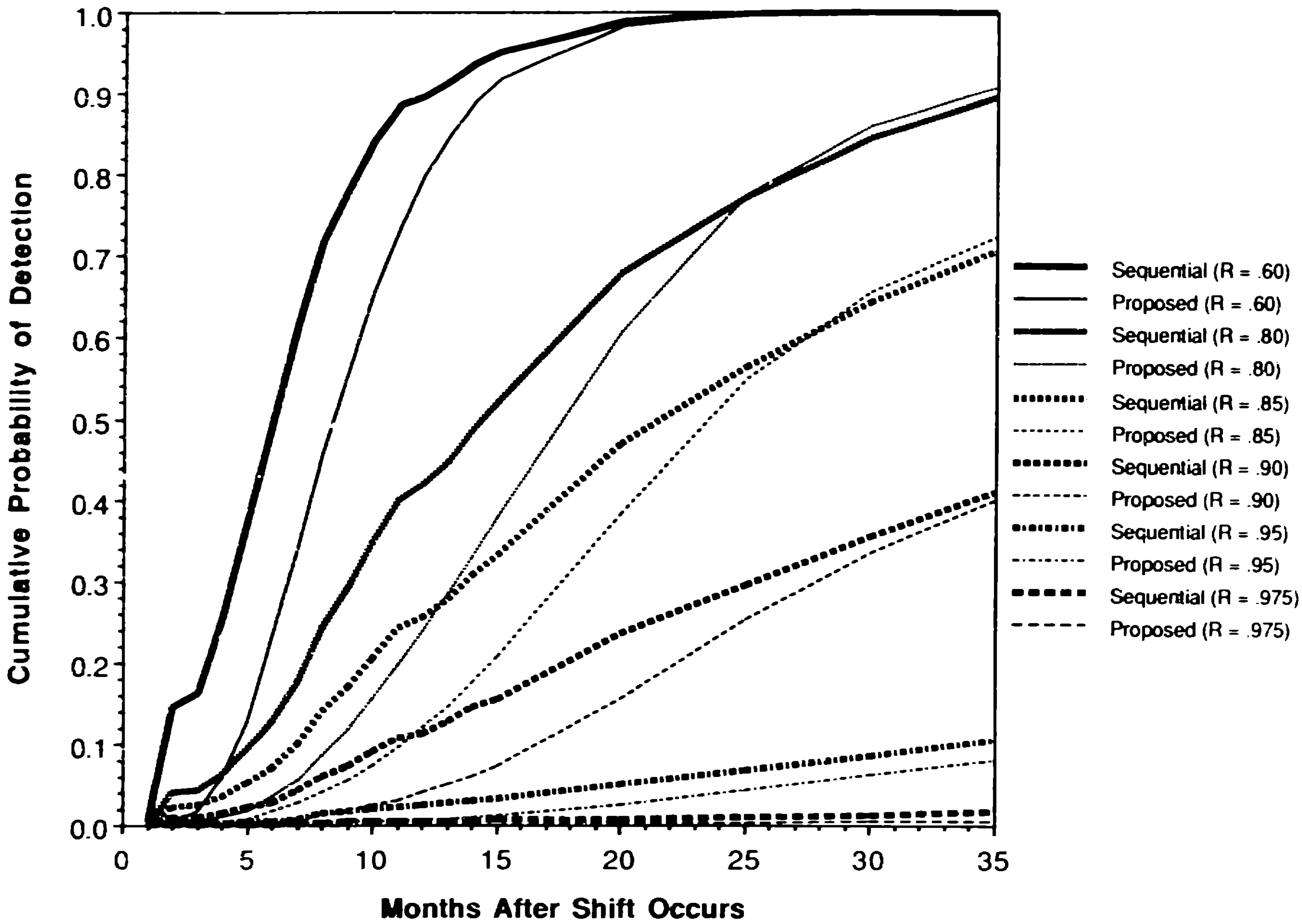


Figure 24

Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting Two-Diesel Degradation To R = 80% (Initial Reliability = 95%)

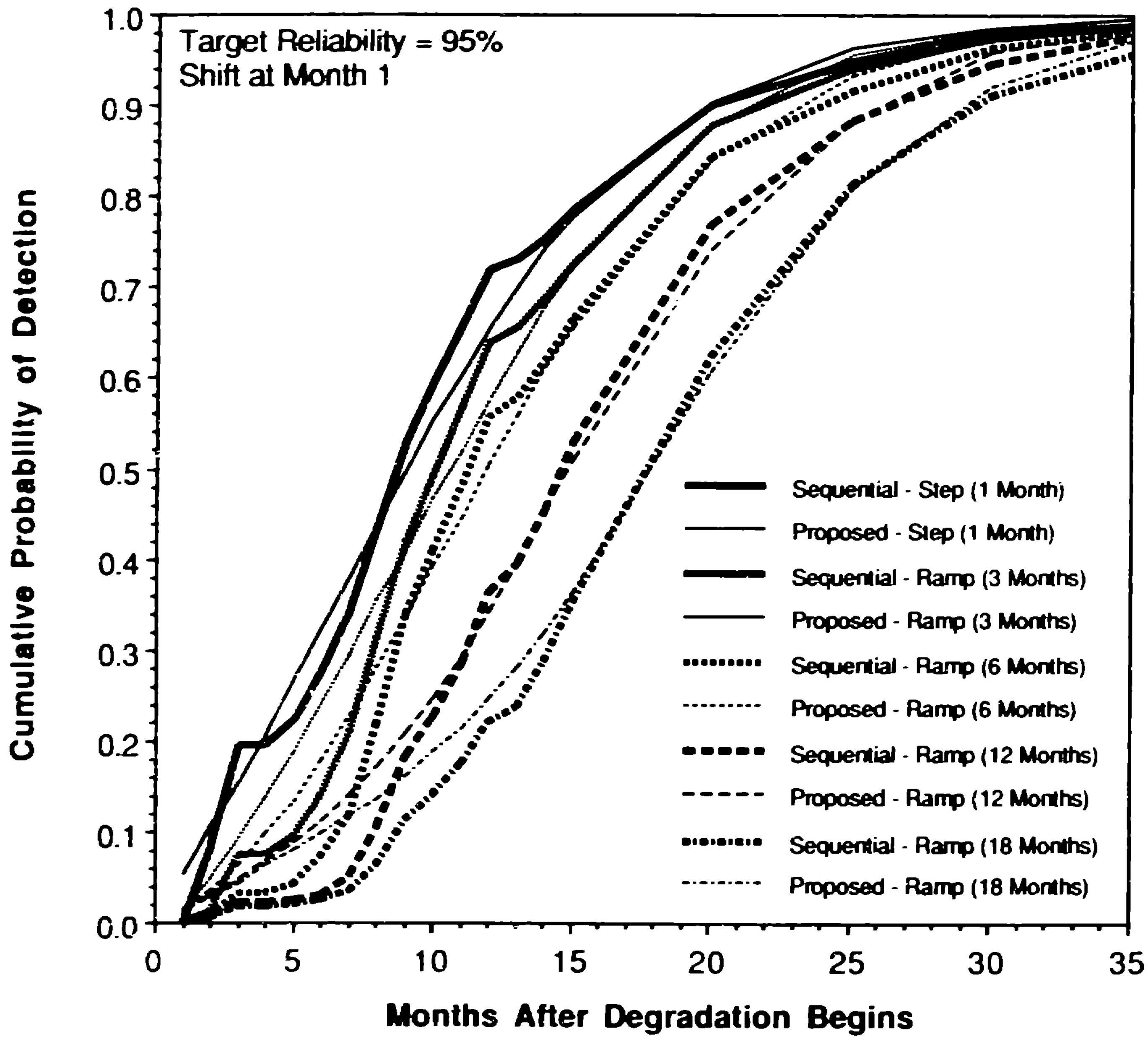
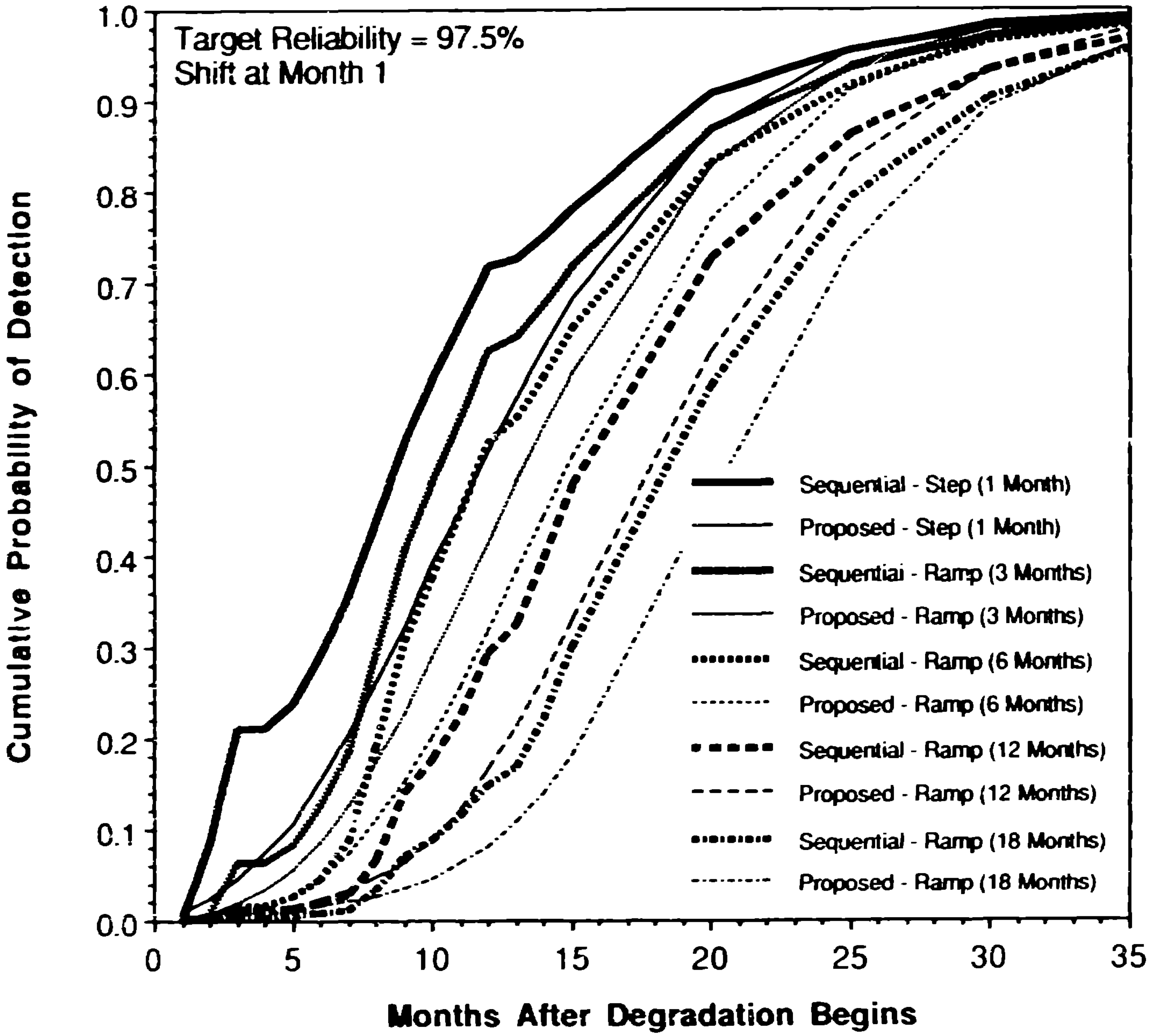
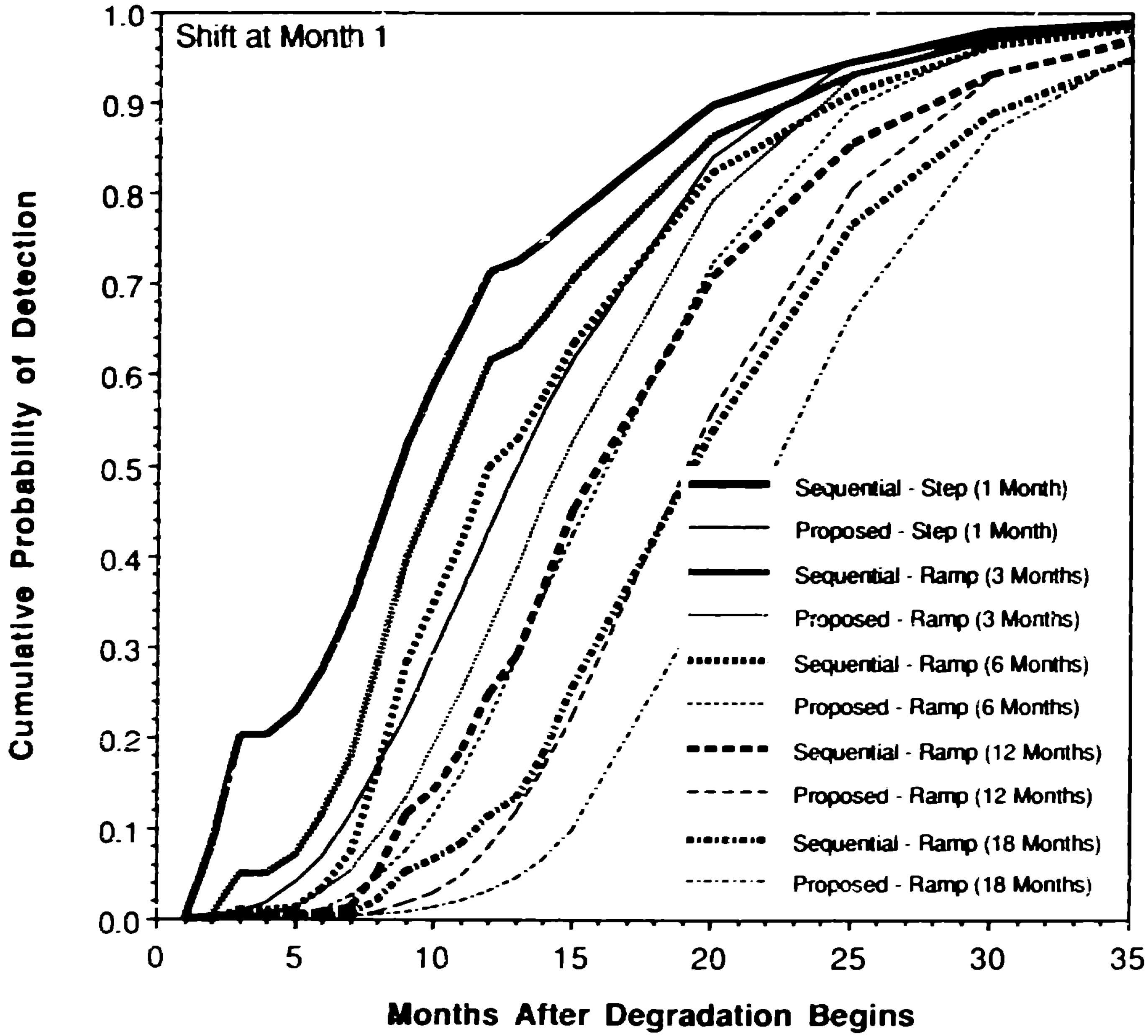


Figure 25

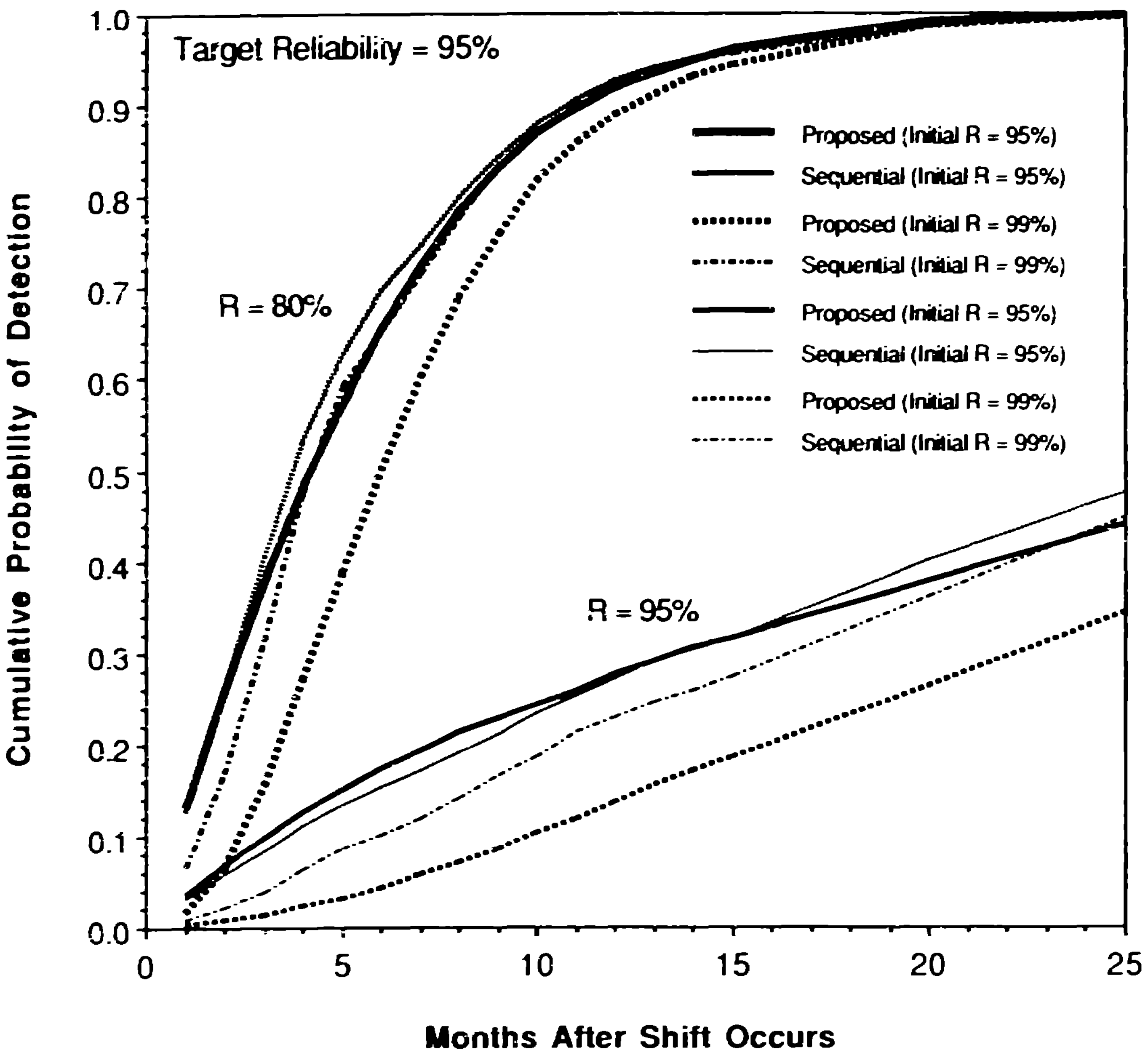
Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting Two-Diesel Degradation To R = 80% (Initial Reliability = 97.5%)



Comparative Performance Of Both The Proposed Problem Diesel (4/25) and Wald Sequential Triggers For Detecting Two-Diesel Degradation To R = 80% (Initial Reliability = 99%)



The Effect Of Initial Reliability On The Performance Of The Proposed Early Warning (3/20) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20



Comparative Performance Of Both The Proposed Early Warning (3/20) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 95%)

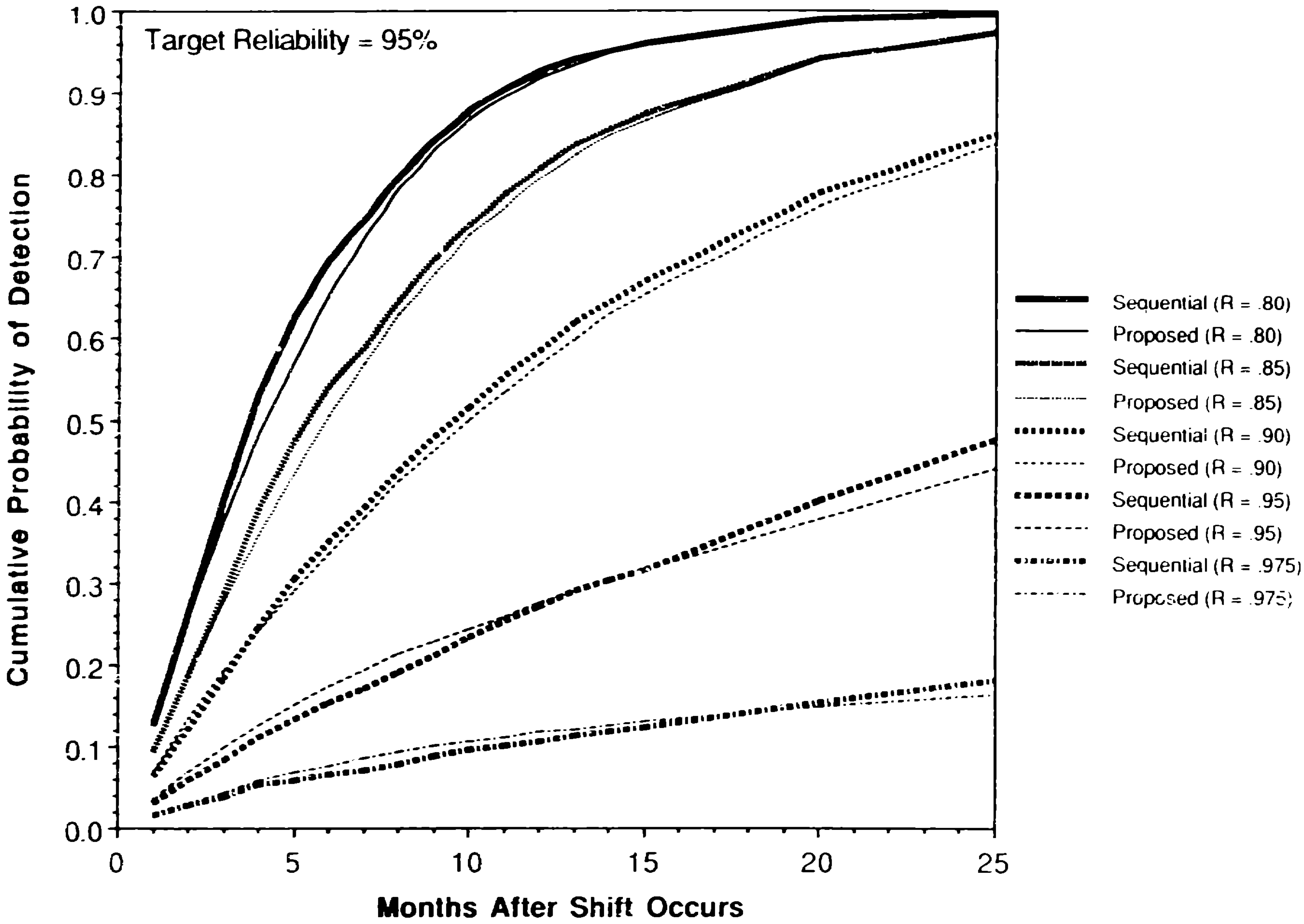


Figure 29

Comparative Performance Of Both The Proposed Early Warning (3/20) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 97.5%)

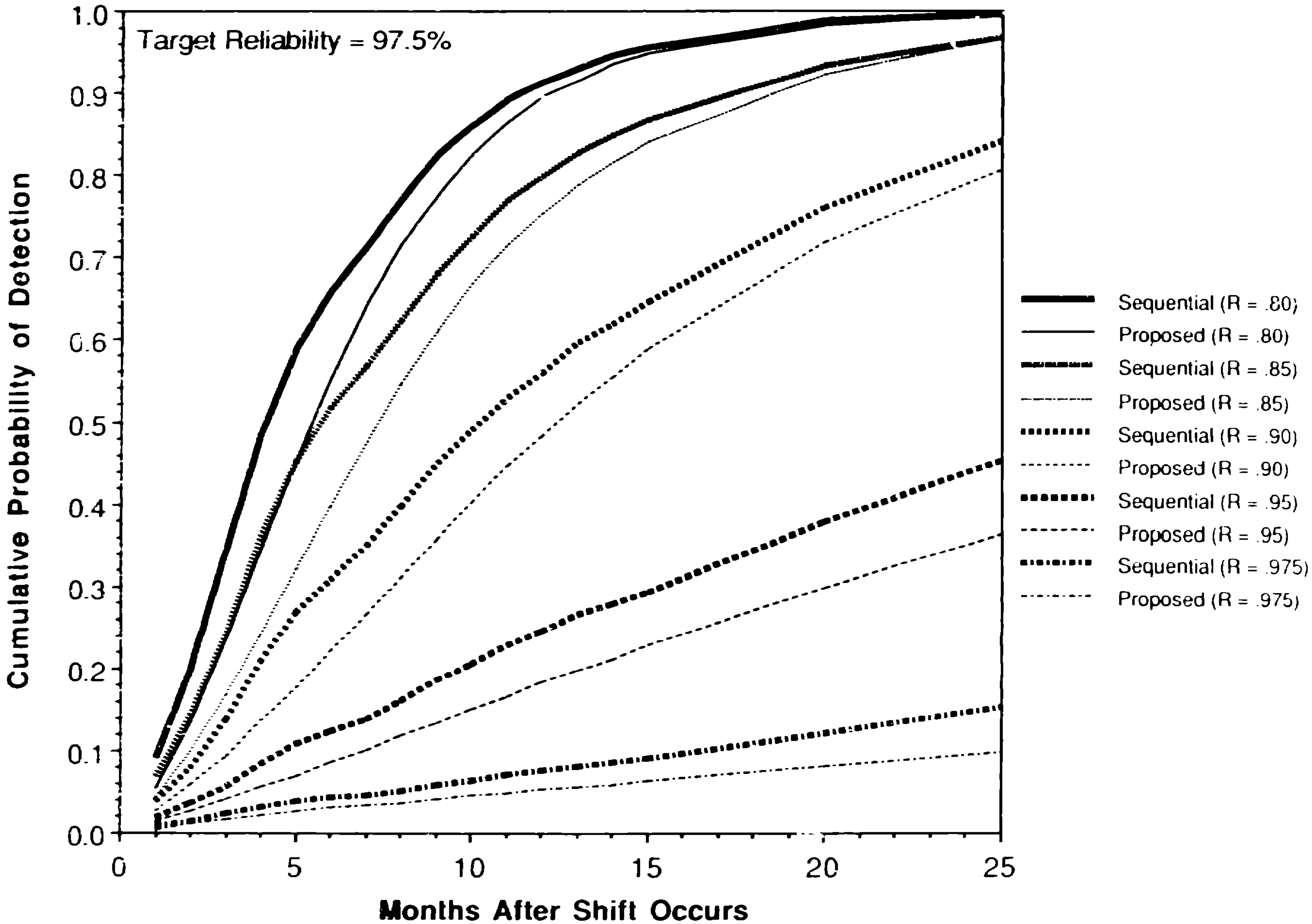
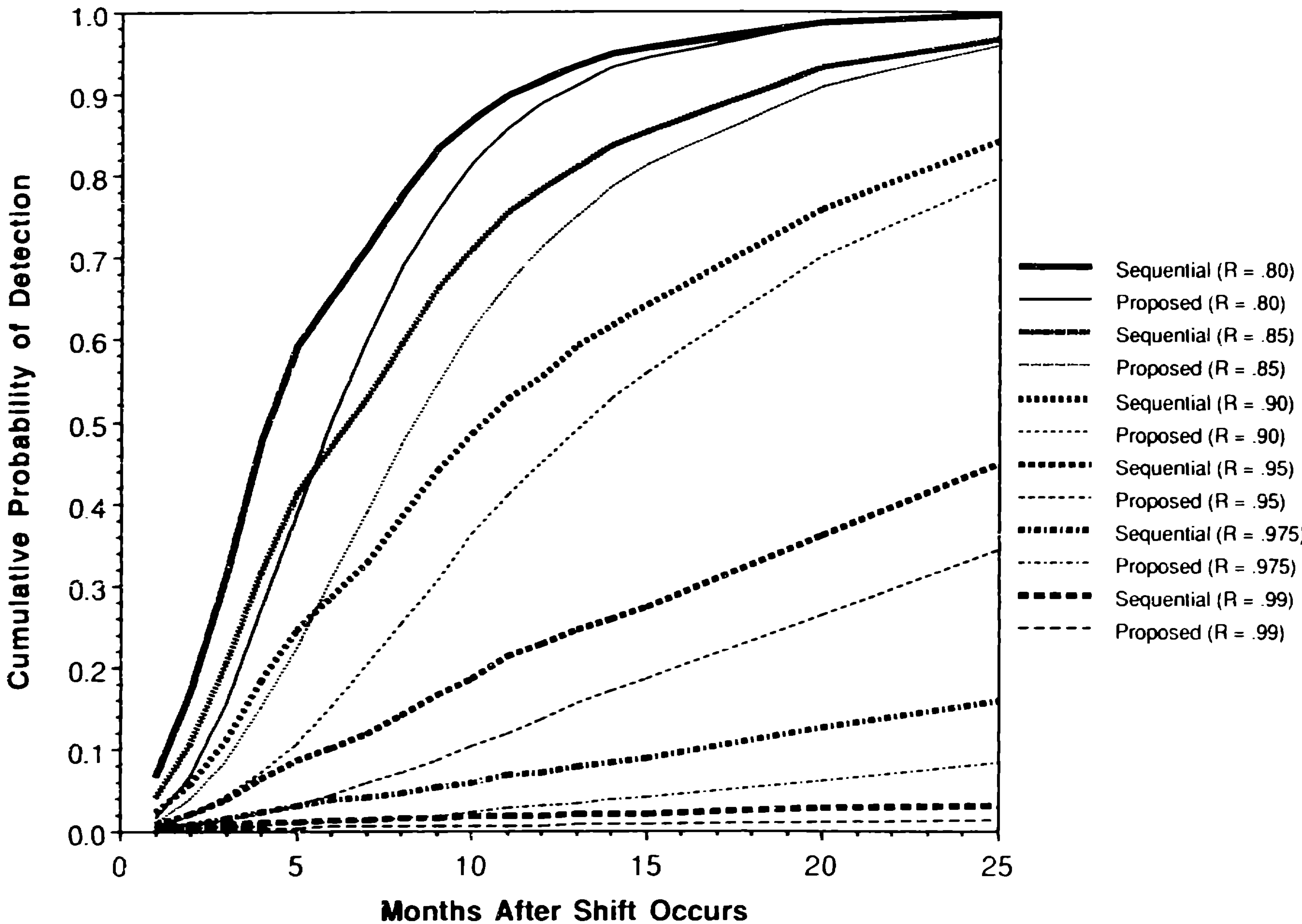
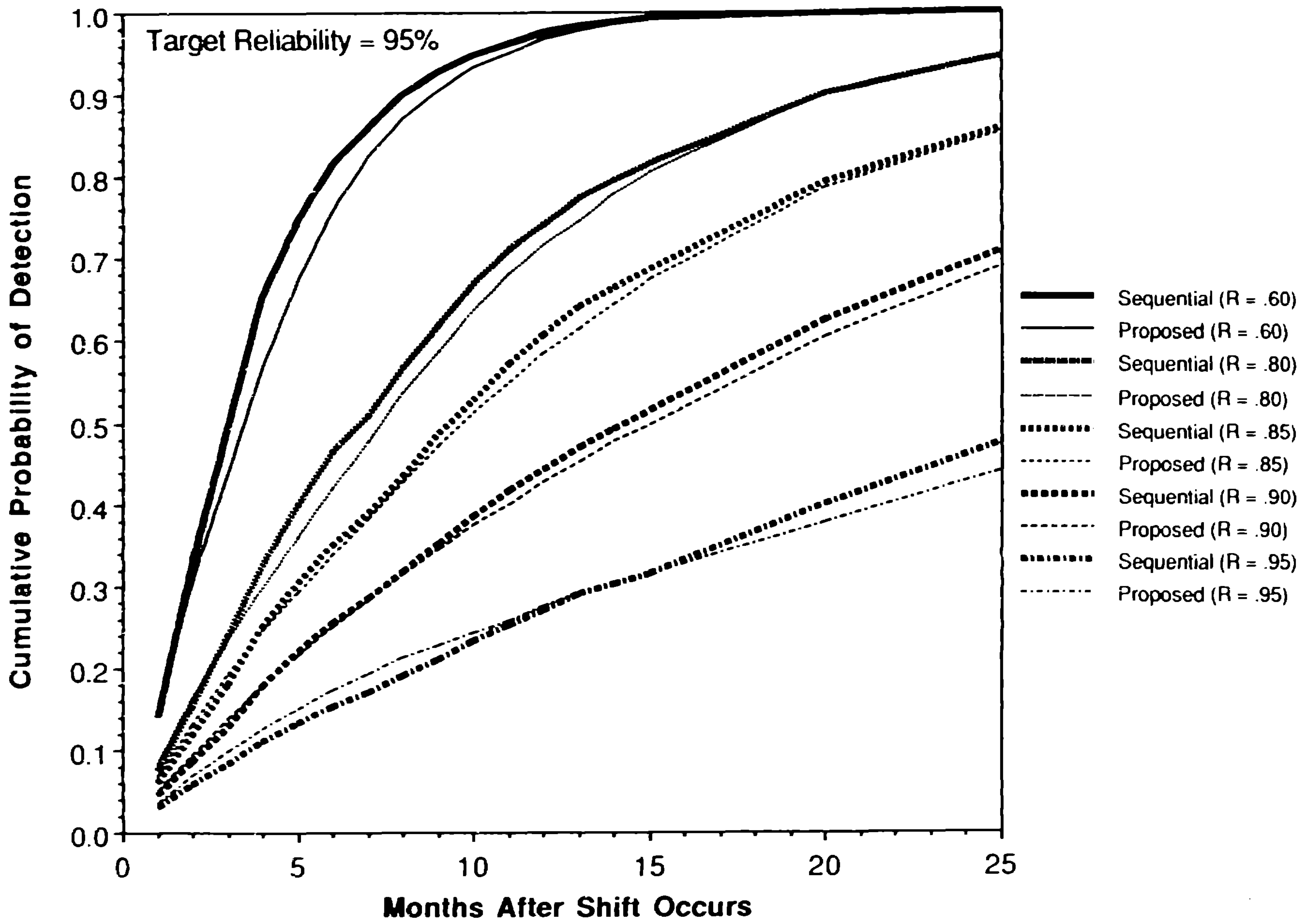


Figure 30

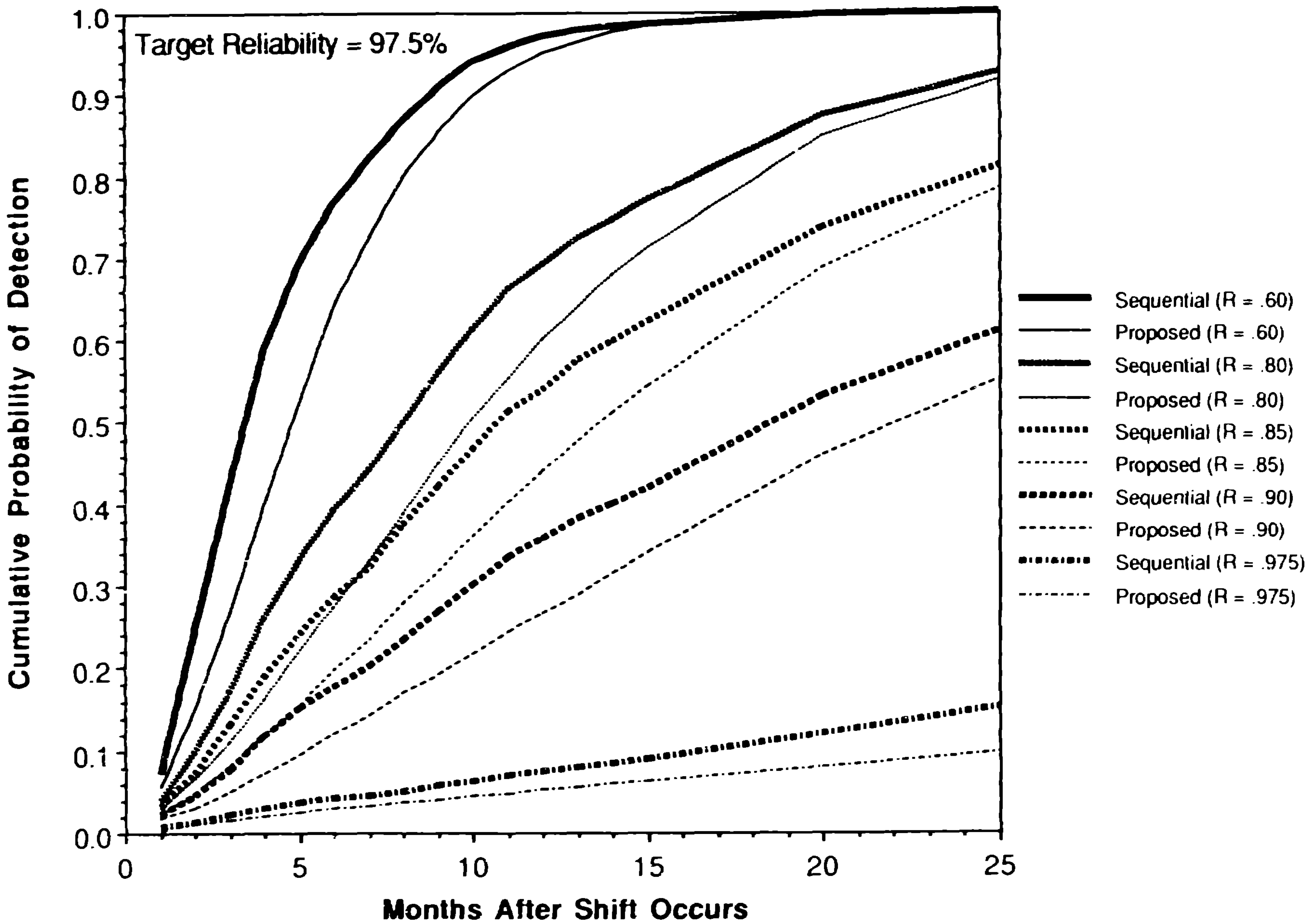
Comparative Performance Of Both The Proposed Early Warning (3/20) and Wald Sequential Triggers For Detecting A Two-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)



Comparative Performance Of Both The Proposed Early Warning (3/20) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 95%)



Comparative Performance Of Both The Proposed Early Warning (3/20) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 97.5%)



Comparative Performance Of Both The Proposed Early Warning (3/20) and Wald Sequential Triggers For Detecting A Single-Diesel Shift To Reliability R At Month 20 (Initial Reliability = 99%)