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Developments in Reliability Models and Methods*

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This paper reviews analytical developments in modeling reliability characteristics for components and systems. Modeling involves definition of failure modes, relevant probability and timing parameters for the modes, and derivation of explicit equations for component and system unavailabilities and failure intensities. Some but not all developments to be discussed were carried out within the DOE-sponsored LMFBR safety program.

MONITORED COMPONENTS

A component is called "continuously monitored" if a failure is immediately revealed, and initiation of repair or replacement is immediate, not tied to a schedule or demand. A failure of an operating component is usually detected by lack of output or expected performance. The status of some standby components can also be monitored by sensing fluid levels, positions of valves, voltages, etc.

Monitored components can be completely characterized by specifying the probability densities of the time to failure, and the time to repair. In addition to a variety of distributions that can be selected, different failure intensity and unavailability characteristics result depending on whether repaired (or replacement) components are old or new, and whether the repair crew and facilities are old or renewed. Exponential distributions consist a

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*This work was carried out under the auspices of the U.S. Department of Energy special case in which the aging of components or maintenance facilities does not matter.

Laplace transformation techniques have been used, when both the component and the maintenance facilities are renewed after each failure, to obtain general equations for the component unavailability (Ref. 1, p. 420) and failure intensity.[2] Some additional relations between these and the repair intensity have been obtained (Ref. 3, p. 193) as an extension or improvement to earlier results.[4] A collection of relationships were recently obtained for components with multiple failed states and initial conditions.[5] Several probabilistic risk models were also developed in Ref. 5, based on the concept of multiple states.

In case that both replacement components and repair facilities are old, and both failure and repair rates are age-dependent, the unavailability has also been analyzed (Ref. 1, p. 418). General equations have been extended to components with multiple failed states and initial conditions, including relations between availabilities and repair and failure intensities.[5] Basic relations and asymptotic behavior (time $\to \infty$) are also being analyzed for components with multiple states when: (1) replacement components are old but repair facility is renewed, and when (2) repair facilities are aging but components are renewed. Explicit analytical expressions and numerical results have been obtained recently for the unavailability and the failure intensity of a binary (two-state) component with a Weibull failure time distribution, a constant (fixed) repair time, and the component initially unfailed.[6]

Stand-by components with failures detected upon demand. Some failures are detected only when the component is demanded to operate. In such a case, repair or replacement can be initiated only after a demand has occurred. The unavailability and the failure intensity have been analyzed in case that both the component and the repair facility are renewed after a failure, and the demands arrive at exponentially distributed random times.[2] It turns out that this case is equivalent to a case with a monitored component, with the repair time made equal to the sum of the waiting time to a demand (detection) and the actual time to repair.

PERIODICALLY TESTED COMPONENTS

Time-dependent and average unavailability equations for periodically tested components have been developed earlier for the case of exponential failure and repair time distributions when the test duration is zero[7] or finite.[8] Practical equations are also available in the case of an exponential failure time distribution with constant (known) test and repair durations.[9] Equations have been obtained with a general failure time distribution when the test and repair durations are constant and components are renewed after each test.[2] A general theory for such renewable components has been developed with arbitrary failure time, test and repair duration distributions, including failures due to testing (detected and undetected) and contributions of true demands.[11] Reference 11 gives detailed results in case of exponential failure time distributions when the test and repair durations have a constant (minimum) portion and an exponential random portion.

Equations have recently been obtained for components with Weibull failure time distributions, allowing replacement components to be new or old after each test or repair.[12] Test and repair durations are still assumed to be constant in Ref. 12, but testing and demand failures as well as failures not detectable by testing are accounted for. Failure rates are also allowed to depend on the number of tests performed.

SYSTEMS ANALYSIS

A number of analytical results have been obtained for simple series, parallel and general m-out-of-n redundancy systems consisting of components with models described above. Explicit analytical results seem to be available only with exponential failure time distributions and constant test and repair durations.

The role of staggering or syncronizing periodic tests have been extensively studied,[13] as well as the roles of undetected failures and common-cause failures.[14] The effects of monitoring and various human error contributions on systems have also been analyzed.[15]

Computer codes have been developed that either contain analytical systems equations (e.g., ICARUS),[16] or numerically construct the system unavailability from analytical component models (e.g., FRANTIC[9] and SAUNA[17]). One limitation of the FRANTIC codes[9,12] is that they require the system unavailability as an algebraic function of component unavailabilities. To overcome this limitation for complex systems, a decision was made to replace the algebraic subroutine in FRANTIC with an effective and flexible systems analysis code. The programming task was assigned to General Electric that had earlier developed a systems code, PROBCALC.[18] After a successful completion of the first version[19], FRANTIC-II and several additional features are now being implemented in a combined code FRANCALC.

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