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Assessment of the Availability Impact of Limiting Conditions for Operation in Nuclear Power Plants

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Abstract

This paper presents a computerized model for evaluating the effect that limiting conditions for operation may have on the availability of nuclear power plants. The model accounts for the relevant features of the actual problem, such as the complexity of the engineering safety systems, the specific surveillance procedures for stand-by systems, the allowable out-of-service times in the technical specifications and the inherent uncertainty in the failure and repair times of the components. This paper describes the theoretical features of the model, the characteristics of the computer program and an application to a safety system in a nuclear power plant.

Introduction

Most large industrial facilities must operate in compliance with regulatory safety restrictions. In the case of commercial nuclear power plants the technical requirements that administratively constrain the plant operation become increasingly questioned, as there is some general acceptance about a lack of justified rationale behind the definition of the so called technical specifications (Refs. 1-5). These technical requirements, while in principle necessary for the sake of safety, also result in:

- shutdowns, derating and operation transients, with a corresponding reduction in plant availability and efficiency.
- increased manpower devoted to surveillance activities.
- more complex operation of the plant.

It may be possible that relaxation and/or modification of some of these technical requirements could result in an increase of plant availability and/or efficiency with no safety loss, and also in manpower savings. In fact there seems to be an important potential for the avoidance of unneeded expenditures. It is then apparent that new tools as an aid for logical decision making in this area are required. These tools must be able to combine standard risk assessment techniques with availability models that explicitly incorporate the effect of technical requirements.

Technical requirements for commercial nuclear power plants include 1) limiting conditions for operation (LCOs), 2) surveillance testing requirements, 3) safety system set point limits, and 4) administrative controls. The work reported in this paper basically addresses the first two categories.

A comprehensive approach to this problem should integrate its most relevant aspects: risk, spurious trips and regulatory unavailability, with each aspect requiring a different model. The term regulatory unavailability will be used here to describe the total or partial unavailability of a plant having its origin in regulatory restrictions exclusively.

In the very recent years the industry has started a major effort to improve the technical specifications (see refs. 1-3). Developed methods are based on probabilistic analysis tools and generally they try to demonstrate that no significant risk is added if a technical specification is relaxed. The risk is their main target, rather than the economical impact through availability models. In fact good risk models can be found elsewhere in the technical literature and they can be directly used in the analysis of the kind of systems addressed in this paper. Extensions to determine the probability of spurious trips have conceptually no difficulty. However a good model for the evaluation of the regulatory unavailability caused by LCOs (Limiting Conditions for Operation) is not available and this paper concerns the development and computer implementation of a prototype of such a model. Reference 5 is an interesting approach to the same problem, but its Monte Carlo simulation method lacks some of the realistic features that are included in the model presented here.

The work reported in this paper is part of a major effort by an electric utility to develop advanced availability analysis methods and to build comprehensive reliability data bases concerning their generation facilities. This regulatory availability model will eventually be integrated in a global approach to assess availability improvement actions in power plants (Ref. 6).

Detailed statistical analysis of historical data is still needed to determine the relative importance of the several possible effects of regulatory restrictions on plant availability, in particular the plant shutdowns and deratings directly caused by violation of the LCOs. In any event the model described in this paper allows the user to predict the expected value of the plant equivalent unavailability caused by violation of a particular LCO and to examine the main trade-offs involved under an availability viewpoint.

Economic Impact of Regulatory Unavailability

The economic impact of the regulatory unavailability caused by a particular LCO can be stated as

$$CU = CS.\int_0^T w_A(t).MTTO(t).dt \qquad (1)$$

where

CU is the unavailability cost of the LCO during the considered time interval 0,T .

CS is the substitution cost of the energy not served by the plant because of the considered regulatory unavailability.

$w_A(t)$ is the probability of activation of the LCO per unit time at time t.

MTTO(t) is the mean time to operation or, in other words, the expected duration of the unavailability caused by the LCO. This includes the time from LCO activation to operation of the plant in the same conditions prior to the LCO occurrence. See in Fig. 1 the relation between the time to operation TTO, the time to repair TTR and the allowed outage time AOT specified by the LCO.

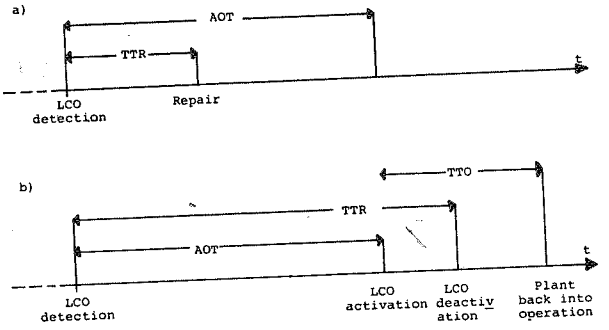

Figure 1. Application Cases of LCO: a) No Regulatory Unavailability, b) Regulatory Unavailability.

Modeling issues

A regulatory availability model must be able to compute the probabilistic parameters $w_A(t)$ and MTTO(t) in eq. (1) at any moment during the time interval of interest. The proposed method to perform these calculations will be described in this section. However the necessity of using a separate regulatory availability model will be shown first with a simple example.

Consider the simplified model of the instrumentation logic of a safety system in Fig. 2. In normal conditions (Fig. 2.a) a trip signal through any of the two channels and the 1/2 voting logic activates the actuator. Figs. 2.b, c and d show the fault trees for the risk model (i.e., no operability of the safety system), the spurious trip condition and the regulatory unavailability (with the LCO requiring both channels to be operative), respectively. Note how "fail dangerous" failures have been considered in b, "fail safe" failures in c and any detected failure in d. It must be concluded that different models with also different probabilities for the basic events are required for each application.

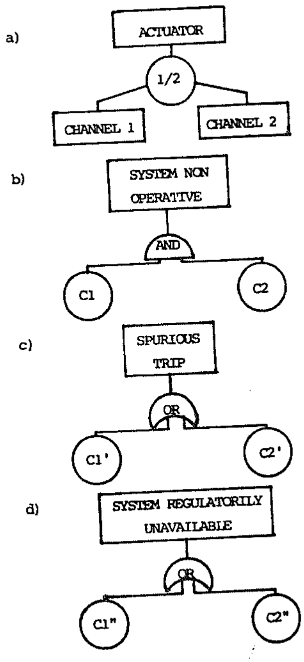

Fig. 2. Instrumentation logic example: a) Working logic, b) Risk model, c) Spurious trip model, d) Regula tory availability model.

Main characteristics of the model

The model accounts for the following realistic fea tures of the actual regulatory unavailability problem:

- Complexity of the engineering safety systems. Fault trees are used as needed to obtain the boolean expre sion of the LCO in terms of minimal sets of the elementary component failures.
- Specific characteristics of stand-by systems, wherel their unavailability critically depends on the surv llance requirements: procedures and time intervals explicitely accounted for in the model.
- Explicit modeling of the allowed outage time AOT, o time that is allowed to pass between the detection the LCO condition and the LCO activation, i.e., the actual realization of its regulatory consequences. The numerical value of the AOT may critically affe the unavailability impact of the LCO. It is assumed that there is a unique AOT for each LCO, regardless of the status of other LCOs.
- The existing uncertainty in the times to failure ar times to repair of the elementary components of th system. Weibull distributions are used in the curr version of the model but there is no conceptual di ficulty in using other distributions.
- Both periodically inspected and continuously monit ed components can be jointly considered by the mod
- Detection of LCOs not only requires the existence the corresponding failures but also that the failu be known by the plant personnel. In periodically i spected components the detection may only happen a particular times. The model accounts for the spec

test scheme of each component; in this way the moments where the LCO may be detected are precisely identified.

- The repair model for a particular occurrence of a LCO takes into account the repair status of the several components involved at the LCO detection time, i.e., repair already under way or just started.

Basic computational procedure

The procedure to compute $w_A(t)$ and MTTO(t) as needed in eq. (1) has the following basic characteristics:

- Each LCO is described by its minimal cut sets (m.c.s) in terms of elementary component failures. The minimal cut sets can be directly provided or, if desired, a fault tree description of the LCO can be processed in a module of the computer program yielding the minimal cut sets.
- The availability analysis is individually performed for each minimal cut set, with the unavailability impacts being just added to obtain the LCO's impact.
- The procedure of analysis of each m.c.s. carefully combines two different probabilistic measures of the failure of every component involved in the m.c.s. The first measure is the probability of failure detection, $f_{Di}(t)$ for the i-th component, i.e., the probability that the failure of the i-th component is detected precisely at time t. The second measure is the probability of existence of a detected failure of the i-th component, $f_{Di}(t)$, i.e., the probability that at time t the i-th component is failed and this failure is known to the plant personnel. For a m.c.s. consisting of two components C1 and C2, the probability of detection of the LCO can be written as

$$f_{D_{LCO}}(t)=f_{D1}(t)\cdot\tilde{f}_{D2}(t)+\tilde{f}_{D1}(t)\cdot f_{D2}(t)-f_{D1}(t)\cdot f_{D2}(t), \quad (2)$$

which can be trivially extended for m.c.s. of higher order. The minus sign results from considering that detection of a failure affects f_D and also $\tilde{f}_D$ at the same instant of time.

- The individual component models for $f_D(t)$ and $\tilde{f}_D(t)$ have been obtained by suitable modifications of the component models in the FRANTIC code (Refs. 7-9). This method can describe failures which occur at a rate described by a Weibull distribution, failures per demand, common cause failures and failures due to human errors. In addition the effects of test downtimes, repair times, test efficiencies, test bypass capabilities, test-caused failures and test staggering can be modeled. Non-repairaible and continuously monitored components can be also modeled. In FRANTIC the pertinent expression for a particular component is computed at a finite number of appropriate times to produce a pointwise unavailability. These pointwise values are then used as if they were linearly connected to form a continuous curve.
- The probability of detection of a m.c.s. of the LCO may now be evaluated at different times (the procedure is also similar to FRANTIC's) by combining the probabilities $f_D(t)$ and $\tilde{f}_D(t)$ of the involved components using equations similar to (2). Actually the computation is carried out simultaneously with the probability of activation. See Fig. 3 for details.

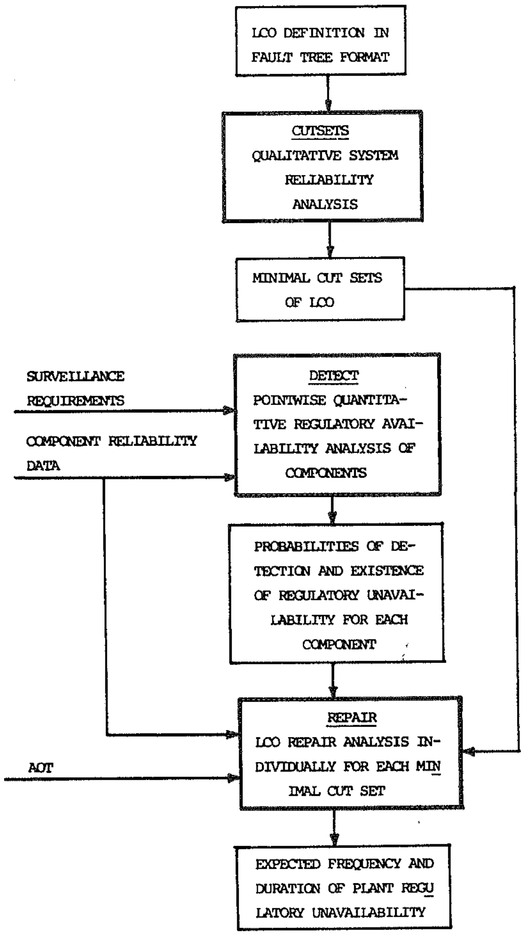

Fig. 3. Overall flowchart of the CAINAD program.

- Whenever the computed probability of detection of a m.c.s. of a LCO is not zero at a time t, it is started the procedure to determine the probability of activation of the LCO at time t+AOT, w_A(t+AOT), and the expected duration of the plant unavailability, MTTO(t+AOT). The calculation of w_A and MTTO results from an analysis of the repair process of the components involved in the active LCO. The repair analysis takes into account the expected repair condition of these components at the LCO detection time, and the inherent uncertainty of any repair process.
- Note that an inconsistency exists in the procedure just described. The probability of detection of the LCO is computed using the same basic approach employed in FRANTIC, where the repair times are deterministic, i.e., their values are fixed a priori. However, the repair analysis yielding w_A and MTTO is probabilistic, since the comparison between AOTs and TTRs (see fig. 1) is critical to the existence of plant unavailability. The simplification introduced in the detection part can be justified on several grounds: a) LCO detections involving MTTR<TTR>STI (surveillance inter

val times) will be missed, but the error will be very small if MTTR≪STI, as it usually is. In any event this can be partly corrected by running the program several times with different sets of MTTRs. b) The main objective of the model, i.e., analysis of alternate AOT values and of different surveillance procedures, is satisfactorily met even if the computed regulatory unavailability is in small error. c) the procedure for the detection part is equivalent to the one used in FRANTIC; in this way the core of the program is based on a well known and industry-wide accepted computer code.

Probability of detection of a LCO

It has been already shown how the probability of detection of a m.c.s. of a LCO can be computed at any instant t from the functions $f_D(t)$ and $\tilde{f}_D(t)$ of all the components involved in the m.c.s. It remains to describe how to obtain $f_D(t)$ and $\tilde{f}_D(t)$ for any given component.

The reader is assumed to be familiar with the procedures used in the FRANTIC code to compute the unavailability of a component subject either to periodic testing or to continuous monitoring. In this work the FRANTIC version known as FRANTIC-II-MIT (see Ref. 8) has been used as the starting point.

The basic idea is very simple, although the computer implementation has required much detailed work. The probability of existence of a detected failure, $\tilde{f}_D(t)$, can be obtained by removing in FRANTIC's unavailability expressions all those terms corresponding to hidden unavailability, i.e., failures not manifest to plant personnel during routine scheduled inspections.

Regarding the detection probability, $f_D(t)$, new expressions have been developed from those in FRANTIC. These expressions only account for component unavailabilities that are patent to plant personnel and only at the precise time when they become known.

For continously monitored components the expression for $\tilde{f}_D(t)$ is simply

$$\tilde{f}_D(t) = q_{detectable}(t) \tag{3}$$

where the failure rate of undetectable failure modes of the component has been set to zero in the expressions used in FRANTIC (Ref. 7-9). Although the original expressions in ref. 7-9 could have been used, new analytical expressions have been developed for q(t). These expressions yield excellent approximations to the exact expressions and they are much more efficient to compute (Ref. 9).

Once $\tilde{f}_D(t)$ is known, the probability of failure detection $f_D(t)$ can be obtained as

$$f_D(t) = \lambda_{detectable}(t) \cdot (1 - q_{detectable}(t)) \tag{4}$$

where only detectable failure modes are included in the failure rate $\lambda_{detectable}$.

For periodically inspected components the probability of component failure detection $f_D(t)$ has been lumped into just two instants of time within each maintenance cycle: the beguinning and the end of the testing interval. In the first instant all the immediately detectable failures that may occur since the last inspection and during the eventual prior repair are detected. In the second instant detectable failures that may arise from the testing activities are detected. Two Dirac deltas of the appropriate magnitude is all that is needed to model $f_D(t)$ in this case.

The value of $\tilde{f}_D(t)$ is zero during the time between inspections and equal to the time integral of $f_D(t)$ during the testing and repair time intervals.

Probability of activation of a LCO

The problem being addressed now is that of a m.c.s. of a LCO being detected at time t-AOT with an AOT prescribed by the LCO. It is desired to compute the probability $w_A(t)$ that the LCO will be activated, that is, the probability that none of the components involved in the m.c.s. will be repaired before the time t.

Making use again of the example of the m.c.s. that consists of only two components C1 and C2, a simple expression for $w_A(t)$ can be written as

$$\begin{aligned} w_A(t) = {} & \tilde{f}_{D1}(t-AOT) \cdot f_{D2}(t-AOT) \cdot R(t, TR_1, TR_2=0) + \\ & + f_{D1}(t-AOT) \cdot \tilde{f}_{D2}(t-AOT) \cdot R(t, TR_1=0, TR_2) - \\ & - f_{D1}(t-AOT) \cdot f_{D2}(t-AOT) \cdot R(t, TR_1=0, TR_2=0) \cdot dt \end{aligned} \tag{5}$$

where $R(t, TR_1, TR_2)$ is the probability that C1 and C2 will not be repaired by time t, given that at time t-A both were failed and that they had already been under repair for a time TR_1 and TR_2, respectively. Assuming complete independence between the repair processes of both components

$$R(t, TR_1, TR_2) = R_1(t, TR_1) \cdot R_2(t, TR_2) \tag{6}$$

If the possibility of occurrence of additional re pair-failure processes for the i-th component within time interval [t-AOT,t] is neglected, then (see fig.

$$\begin{aligned} R_i(t, TR_i) & = \frac{G_i(t-(t-AOT-TR_i))}{G_i(t-AOT-(t-AOT-TR_i))} = \\ & = \frac{G_i(AOT+TR_i)}{G_i(TR_i)} \end{aligned} \tag{7}$$

where $G_i(t_2 - t_1)$ is the probability that the i-th com nent will not be repaired by the time t_2 given that repair started at time t_1. Equation (5) then becomes

$$\begin{aligned} w_A(t) = {} & \tilde{f}_{D1}(t-AOT) f_{D2}(t-AOT) G_1(TR_1 + AOT \\ & G_2(AOT) / G_1(TR_1) + f_{D1}(t-AOT) \tilde{f}_{D2}(t-AOT \\ & G_2(TR_2 + AOT) G_1(AOT) / G_2(TR_2) - f_1(t-AOT \\ & f_2(t-AOT) G_1(AOT) G_2(AOT) dt \end{aligned}$$

Expressions have been obtained and implemented in the computer program that generalize equation (8) for m.c.s. with any number of components (Ref. 6).

The remaining difficulty with (8) is that the times TR_i are not uniquely defined, since the failure and subsequent repair of the i-th component may have occurred in several occasions in the past. Therefore expression (7) must be replaced by

$$h_i(t) = \int_{TR_i=0}^{TR_i=\infty} p(t-AOT,TR_i).\frac{G_i(TR_i+AOT)}{G_i(TR_i)}.dTR_i \qquad (9)$$

where $p(t-AOT,TR_i)$ is the probability that the repair of the i-th component started at time $t-AOT-TR_i$ given that it is failed at t-AOT.

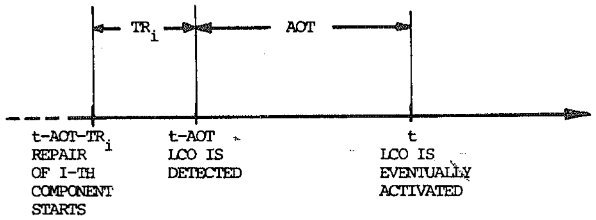

Fig. 4. Computation of $R_i(t,TR_i)$

For periodically inspected components it can be shown after some analytical work that in all practical instances $h_i(t)$ reduces to $R_i(t,TR_i)$ with TR_i corresponding to the last possible scheduled repair.

For continuously monitored components $p(t-AOT,TR_i)$ can be written as

$$p(t-AOT,TR_i) = f_D(t-AOT-TR_i).G(TR_i)/ \\ /\int_0^{\infty} f_D(t-AOT-u).G(u).du \qquad (10)$$

which can be used in (9) yielding

$$h_i(t) = \int_0^{\infty} f_D(t-AOT-u).G_i(AOT+u).du/ \\ /\int_0^{\infty} f_D(t-AOT-u).G(u).du \qquad (11)$$

Expected duration of unavailability

The expected value MTTO(t) of the duration of the unavailability caused by a LCO comprises two different phases of the process. The first phase consists of the time still needed after the activation of the LCO to repair the failed components of the considered m.c.s. of the LCO. The second phase concerns the time required to restore the plant back into operation. It will be assumed that the expected duration of the second phase can be separately estimated for each LCO and therefore will not be considered here. The expected duration of the first phase $MTTO_1(t)$ results from the following analysis of the repair process.

Consider again the example of the m.c.s. of a LCO with the two components C_1 and C_2. Now consider the possibility that failure of C_2 is detected at time $t-AOT-TR_2$ and then failure of C_1 is detected at t-AOT. Consequently the LCO is detected also at time t-AOT, with the probability of activation at time t being

$$w_A(t) = f_{D1}(t-AOT).\tilde{f}_{D2}(t-AOT).G_1(AOT). \\ .G_2(AOT+TR_2)/G_2(TR_2)$$

Then for a time t' > t

$$w_A(t') = w_A(t).\frac{G_1(AOT+t'-t)}{G_1(AOT)}. \\ .\frac{G_2(TR_2+AOT+t'-t)}{G_2(TR_2+AOT)}$$

The desired expected duration is in this case

$$MTTO_1(t) = \frac{1}{w_A(t)}\int_{t'=t}^{t'=\infty} -\frac{d}{dt'}w_A(t'). \\ .(t'-t).dt' = \frac{1}{G_1(AOT)G_2(TR_2+AOT)}. \\ .\int_{u=0}^{u=\infty} -\frac{d}{du}(G_1(AOT+u)G_2(TR_2+AOT+u))udu \qquad (12)$$

These expressions can be easily generalized to any number of components and have been implemented in the computer program.

Computer implementation

The aforementioned methodology has been implemented in a computer code named CAINAD (this stands for initials of "Computation of the Regulatory Unavailability", in spanish). CAINAD will be used to assess the importance of LCOs as a contributing factor to plant unavailability and also to evaluate, under an availability viewpoint, modifications in the surveillance requirements and/or allowed outage times of stand-by safety systems.

Currently CAINAD can be linked together with FRANTIC-II-MIT, thus allowing the user to compute either the actual or the regulatory unavailability of a system, with most of the data being common to both programs. The input data required by CAINAD can be classified into three groups: a) a fault tree description of the LCO, b) component reliability parameters, including failure rates (time and demand related, common cause failures and human errors), repair and monitoring characteristics (see Refs. 7-9) and c) relevant technical specifications, such as surveillance requirements and allowed outage times. The program calculates the global measures of regulatory unavailability impact on the plant: expected values for the duration and frequency of regulatory unavailability occurrences. Less aggregated availability measures, concerning individual minimal cut sets or components can also be optionally obtained.

Figure 3 shows the overall flowchart of the program, which consists of three main modules. The CUTSETS module (already in the FRANTIC-II code) is used to obtain the minimal cut sets for a LCO defined in fault tree format. The detailed availability analysis of the components is performed by the DETECT module, which obtains the pointwise representation of the probabilities of detection and existence of regulatory unavailability for each component. DETECT is very similar to FRANTIC regarding the basic logic and structure of the program. The REPAIR module combines the information provided by DETECT and CUTSETS and uses its own models for the repair process to produce the probability of activation and the expected duration of the LCO at each considered instant of time. These computations are carried out in parallel for all the minimal cut sets. Time integration of these magnitudes (by the trapezoidal rule or by standard integration subroutines when appropriate) yields the desired value of expected unavailable time attributable to the LCO during the considered time interval (see eq. 1).

The CAINAD program is written in FORTRAN and has been implemented in a Data General Eclipse MV/8000 computer. The program has 4200 lines of FORTRAN code and the object module requires 90 K of main storage when dimensioned for 3000 minimal cut sets of up to fifth order, when linked together with FRANTIC II-MIT.

Application

The program has been applied to the analysis of a particular instance of regulatory unavailability in the main steam isolation subsystem (MSIV) of the nuclear steam supply system of C.N. Cofrentes, a General Electric BWR//6 power plant presently in operation. The main objective of this application was to exercise the methodology and test the code. Other applications are presently under way.

The only LCO analyzed concerns the instrumentation of the MSIV. The MSIV trip logic is of the 1 out of 2 twice type, therefore requiring 4 channels. Each channel has the same seven trip functions, each one of these with and independent sensor, trasmitter and trip unit per channel.

According to the technical specifications any channel found inoperable must be placed in the tripped condition in 1 hour, unless it can be restored to operable status before that time. When application of the same policy with a second channel would cause the trip function to occur, an AOT of 2 hours is permitted before the regulatory action (hot shutdown in 12 hours and cold shutdown in 24 hours) be taken. Therefore detection of this particular LCO occurs when 2 channels belonging to different trip systems are found to be inoperable. If the inoperable situation persists after the AOT the LCO is activated.

A fault tree for the regulatory unavailability of the instrumentation of the MSIV was prepared. In order to decrease the number of resultant minimal cut sets the basic failures of the sensor, the transmitter and the trip unit for each trip function at each channel have been combined into a single failure. This does not have any effect on the accuracy of th final results. The fault tree has 100 gates and 88 basic events, all of them correspondin to component failures.

Application of CUTSETS yielding 784 secon order m.c.s. and 1344 third order m.c.s. Those m.c.s. of higher order were neglected. The contribution of the third order m.c.s. to the regulatory unavailability was later found to be negligible.

Failure and repair data were obtained fr several sources, including equipment-specific technical documentation, industry general dat (particularly NPRDS) and similar studies such as references 2 and 3. Typical MTTR values of 1 hour were used and Weibull probability distributions with $\beta=1.5$ were chosen. The progra was run for three different values of AOT: th actual one of 2 hours, and also 1 hour and hour, in order to test the sensitivity of th results to changes in this critical paramete A test interval of 1 month was taken and testing of all components was assumed to occur simultaneously.

Table I summarizes the results of the tree test runs, where the time to restore th plant into operation after the LCO has been deactivated is not accounted for. The averag value of the LCO deactivation times $MTTO_1$ ha been computed only for the second order m.c. The numerical results show the small expecte regulatory unavailability impact of this LCO and also the potentially dramatic consequen of modifying the value of the allowed outag time.

TABLE I - RESULTS FROM CASE EXAMPLE

AOT (hr)	$\int_0^{1yr} w_A.MTTO_1.dt$ (hr)	$\int_0^{1yr} w_A.dt$ times/yr	$MTTO_1$ (hr)
2	0.0008	0.003	0.27
1	0.0245	0.071	0.35
0	0.2433	0.379	0.64

Conclusions

This paper presents a new methodology to evaluate the economic impact of regulatory unavailability caused by limiting conditions for operation (LCOs) in commercial nuclear power plants. The methodology has been implemented in a computer program named CAINAD and successfully tested in realistic applications. The proposed method fills a gap in the currently available procedures of assessment of technical specifications, which are mostly focused on the risk impact side. Careful evaluation of historical data and thorough analysis of LCO parametes with risk and regulatory unavailability models will provide the technical and economical basis for a sound revision of the current definition of technical specifications.

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