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A GENERIC MODEL FOR PROBABILITY OF OPERATION WITH A MIS-ORIENTED FUEL BUNDLE

by

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SUMMARY

A generic model was developed based on the SIL-347 verification procedure to quantify the probability of operating a reactor with a mis-oriented fuel bundle (MOFB). An event tree was constructed to find this probability using human error rates from NUREG/CR-1278. The results show that the probability of operating the reactor with a MOFB is 8.5×10^{-5} per cycle. This probability of operation with a MOFB is lower than the probability of a large break LOCA (i.e., 10^{-4} per year).

INTRODUCTION

One potential type of bundle loading error that can occur is the mis-oriented fuel bundle. In this case, the bundle is in the correct location but is rotated by 90 or 180 degrees. In reactors where the water gaps are non-uniform around the bundle or where the rod enrichment distribution is not quadrant-symmetrical, rotation can cause increases in local rod power through increased moderation. In C and S lattice reactors the rotation results in non-uniform water gaps and produces similar increases in local rod power. Of the 17 plants responding to a survey on rotated bundles, there have been 96,137 bundle insertions to date. There are 22 known cases of a rotated bundle being discovered and corrected during core verification (i.e., prior to plant operation). Because of these incidents, the mis-oriented fuel bundle has received increasing attention over the years and the SIL-347 verification procedure has been established.

In this paper, a generic model based on the SIL-347 verification procedure has been developed to quantify the probability of an undetected mis-oriented fuel bundle using generic human reliability rates. This model can be modified to factor in plant-specific procedures. An event tree was developed to quantify the probability. The branch points on the event tree that represent the probabilities of success and failure were obtained using the methodology of NUREG/CR-1278.

ACCIDENT PROGRESSION AND EVENT TREE DEVELOPMENT

The initiator for operating a reactor with a mis-oriented fuel bundle is an operator placing the bundle into the core in a mis-oriented position. The next step in the accident progression is failure to detect the mis-oriented fuel bundle. SIL-347 provides a recommended verification process to detect a MOFB. The SIL-347 verification procedure requires two core scans. One scan is with an underwater TV camera positioned close enough to read the bundle serial numbers on top of the lifting bail (first attribute) and to check the orientation of the bosses (second attribute). The other scan is with a TV camera positioned sufficiently above the core to allow viewing one complete 4 bundle cell for the following four attributes: boss on lifting bail, channel fasteners, channel buttons, and "cells look alike". Two independent reviewers (checkers A and B) are recommended to verify video tapes from the above procedures.

The event tree developed for the mis-oriented fuel bundle is shown in Figure 1. The initiating event frequency is obtained from the result of a survey showing the number of cases of a rotated bundle, but instead of 22 cases, 30 is used for conservatism. After the fuel bundles' placement in the core, the loading operator could observe a mis-oriented fuel bundle. If he detects and corrects the mis-oriented fuel bundle, it is not counted as a mis-oriented event. If he fails to identify the incorrect placement of the bundle, checker A has a chance to detect the rotation error on the low level TV pass from checking either the first or second attribute.

If checker A fails to detect any rotation error, there is a probability that checker B will recognize the MOFB on the low level TV pass from checking the two attributes.

If MOFBs are not identified through the low level TV pass, the high level TV pass using the four attributes will recognize MOFBs. As can be seen on the event tree, branch points appear for both checkers with attributes 1 through 4. In the case where the two checkers fail to identify any MOFB, the end state will be operating the reactor with a mis-oriented fuel bundle.

EVENT TREE QUANTIFICATION

The event tree described in the previous section was evaluated and MOFB probability calculated. The initiating event frequency was obtained based on the 30 rotation errors in 96,137 bundle insertions. This gives an initiating frequency of 3.1×10^{-4}/insertion. Multiplying this probability by the average number of movements per refueling outage (600), the probability of 0.19/outage is obtained. This value represents the combined failure frequency for the events MOFB*E1 (the initiator and event E1 in Figure 1).

For checker A using a low level TV pass, the basic human error probability (HEP) for the first attribute is taken from Table 20-22 in NUREG/CR-1278. Item 1 of this table gives the HEP for failure to check routine tasks (in this case, reading the bundle serial number). The HEP is 0.1, and the error factor (EF) is 5. The values in the reference are interpreted as median values of a log normal distribution. For this analysis, the HEP is converted to a mean value because the initiating event frequency is given as a mean value. From NUREG/CR-2728, an equation for converting median values to means for a log normal distribution is:

$$\text{Mean} = \text{Median} * \text{EXP}[(\ln(\text{EF})/1.645)^2/2].$$

The mean value for the HEP for event E2 in Figure 1 using the above equation is 0.16. For event E3, which represents checker A checking attribute 2 (orientation of bosses), medium dependency (MD) on the result of his examination of the first attribute is assumed. Even though this is the first time that checker A is checking the second attribute, some dependency is assumed because of the favorable outcome from checking the first attribute. Equation (10-11) for

medium dependency (MD) from table 20-17 in NUREG/CR-1278 is used. It is:

$$Pr=(1+6n)/7,$$

where:

Pr=failure probability to identify a MOFB by checking an attribute
n=human error probability.

Substituting 0.1 for n gives a median value of 0.23. After converting to a mean value, 0.37 is obtained.

Item 8 from table 20-22 in NUREG/CR-1278, which represents checking by a second checker, is used to obtain the basic human error probability for checker B on the low level TV pass for the first attribute (event E4). The value given in the table is 0.5 with an error factor of 5, and the mean value is 0.8. As for checker A, medium dependency is assumed for the second attribute based on the result of the first attribute. Using 0.5 for n in the equation for medium dependency, 0.57 is obtained resulting in a mean value of 0.92.

For checker A on the high level scan for the first attribute (Boss on lifting bail, Event E6), the basic HEP of 0.1 with an error factor of 5 is used. On the high level scan, the operator has a completely different view of the core. However, some dependency exists because of checker A's knowledge that the low level scan has previously been verified by both himself and checker B. Equation (10-10) in Table 20-17 for low dependency is used. The equation is:

$$Pr=(1+19n)/20.$$

Substituting 0.1 for n gives a median value of 0.145. After converting this value to a mean value, 0.232 is obtained as the failure probability to identify a MOFB by checking the first attribute. For event E7, channel fasteners are quite visible on the videotape, and the same HEP of 0.1 is used. Because checker A knows this is the first time that the attribute 2, channel fasteners, is being checked, low dependency rather than complete dependency is assumed. A mean probability of 0.232 is obtained. Channel buttons are more difficult to see than channel fasteners on the videotape. Therefore, a failure probability of 1.0 is assumed for the third attribute. For the fourth attribute ("cells look alike"), the same probability of 0.232 that was used for the second attribute is taken because this is the first time this attribute is checked.

For checker B on the high level scan for the first attribute (event E10), the HEP of 0.5 with an EF of 5 taken from Table 20-22 (for a second checker) is used. A low dependency is assumed on checker B's knowledge that this attribute has previously been checked. Using equation (10-10) in table 20-17 and converting median to mean, a failure probability of 0.84 is obtained. For attributes 2 through 4, Complete dependency is assumed due to the fact that the first checker's inspection was completed and that he did not identify any rotated bundles.

Multiplying the initiating event frequency by the conditional probabilities along the sequence ending in a MOFB gives $8.5x10^{-5}$ per cycle as the probability of operating a reactor with a MOFB. This probability of operation with a MOFB is lower than the probability of a large break LOCA (i.e., 10^{-4} per year).

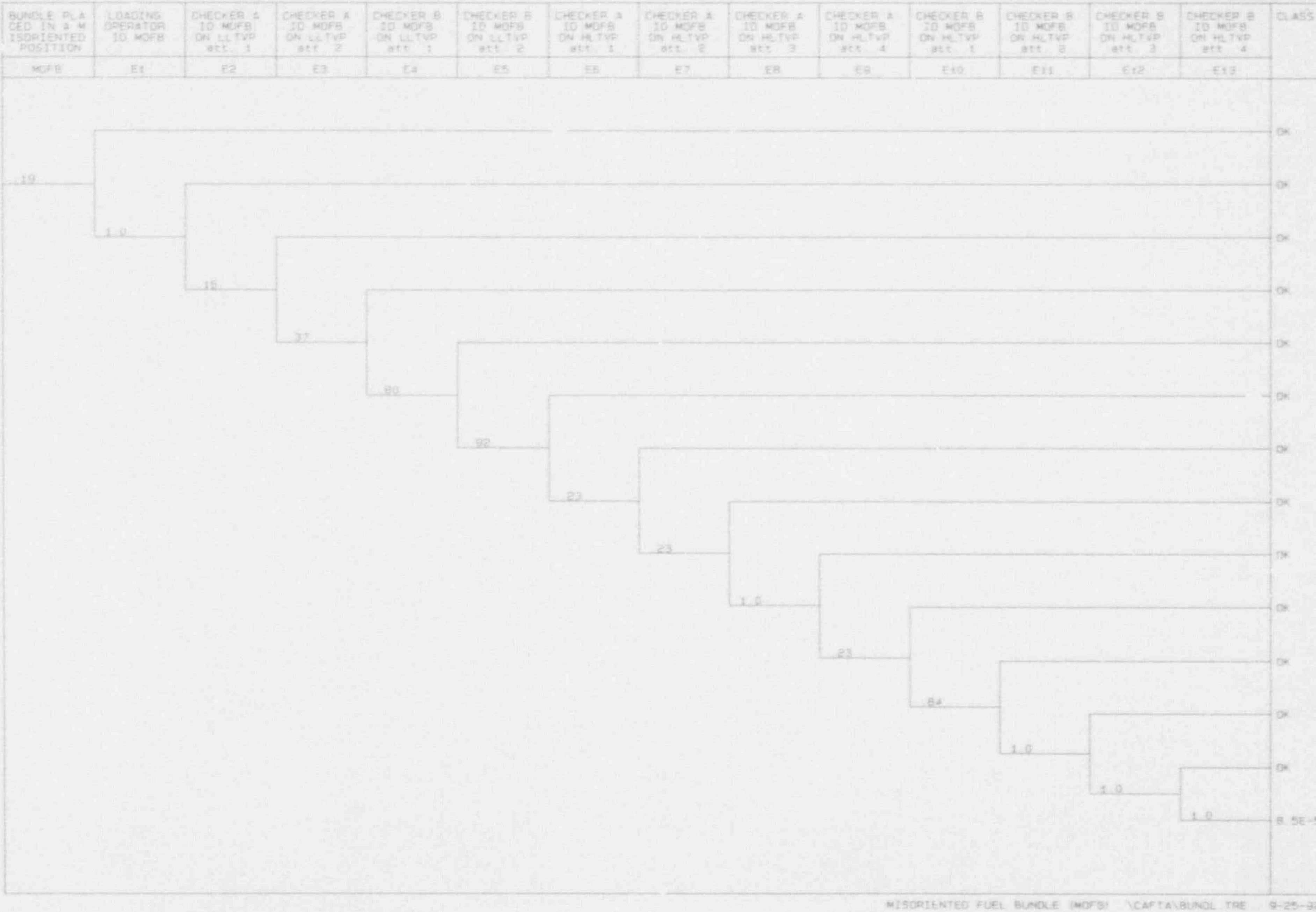

Figure 1 MOFB Event Tree

Attachment 2

Consequences of Operation with a Rotated Bundle

The rotation of a fuel assembly results in a slight axial tilt in the rotated fuel assembly and an azimuthal rotation of the enriched fuel rods in the rotated fuel assembly. The axial tilt of the rotated fuel assembly is toward the control rod position and is caused by the channel buttons and channel fastener contacting the upper grid of the reactor vessel internal structure.

The significant adverse consequences of operation with a rotated fuel assembly are confined to the rotated fuel assembly. The slight axial tilting of the rotated fuel assembly results in an axial variation in the thickness of the water gap between fuel assemblies. The axial variation is zero at the bottom of the fuel assembly and is the greatest at the upper grid contact point; approximately one foot above the top of the fuel column. The major impact is confined to the rotated fuel assembly itself with only second order, insignificant impact on the adjacent fuel assemblies. Thus, the adverse impact is localized to the rotated fuel assembly.

The adverse consequences of operation with a rotated fuel assembly are limited to only a few fuel rods in the rotated fuel assembly. Within the rotated fuel assembly there is a redistribution of power in the fuel rods. This is caused partly by the tilt and partly by the enrichment relocation. The power in some fuel rods is higher and is lower in others. In the D-lattice core, the major impact is at the bottom of the fuel assembly and is the result of the enrichment relocation. The impact of the enrichment relocation is diminished by the tilt at the top of the fuel assembly. In the C- and S-lattice cores, the major impact is at the top of the fuel assembly and is the result of the increase in water gap in the instrumentation corner of the lattice caused by the tilt. The relevant parameter that is affected by the power redistribution is the R-factor because it relates to the critical power (CP) margin. The R-factor for some of the rods in the rotated fuel assembly increases, giving less CP margin. Typically only one to four fuel rods would experience a significant adverse R-factor impact, which reduces the margin to boiling transition for these fuel rods. Extensive thermal-hydraulic testing has shown that boiling transition in some fuel rods in a fuel assembly do not result in boiling transition for other fuel rods in that fuel assembly. This has been confirmed by operating experience at a foreign plant where only a very few fuel rods perforated as a result of an extreme dryout condition.

The coolant flow, power level and power distribution in other fuel bundles in the core are not significantly affected by the performance of the rotated fuel bundle. The fuel assemblies adjacent to the rotated fuel assembly are subject to some power redistribution

as a result of the variable water gap on one face of the fuel assembly but the impact on R-factor is not significant.

Operation with a rotated fuel assembly does not result in a change in the coolable geometry of the fuel assembly. The inlet orificing, lower tie plate, spacers, upper tie plate fuel channel and channel fastener are not affected by the rotation of a fuel assembly in the core. If boiling transition does occur, the nature of the impact is increased cladding temperature in a localized region. Since the thermal margin to dryout on each fuel rod varies from a minimum on the single, most limiting rod to very substantial margin on other rods, most of the fuel rods in the fuel assembly are capable of withstanding the rotated fuel assembly event without reaching their boiling transition limit. Experience in thermal-hydraulic testing of fuel rods in the dryout condition indicates that fuel rod perforation results from extended operation at higher temperatures where accelerated corrosion eventually causes a metallurgical failure of the cladding rather than from spontaneous melting. Therefore, fuel rod perforation is not a forgone event if boiling transition is experienced. But, if perforation does occur, the result is a small opening through which fission products escape, and the basic cladding geometry is not substantially changed. This has been confirmed by operating experience at the above mentioned foreign plant, which, although no fuel assemblies were rotated, did have a few fuel assemblies in which one rod each was perforated due to steady state operation in an extreme dryout condition. Thus, the geometry of the fuel rods in the rotated fuel assembly as well as other fuel assemblies in the core remains coolable.

The adverse consequences of operation with a rotated fuel assembly are detectable and can be suppressed during operation just like leaking fuel rods resulting from other causes. In this context, the adverse consequence is the perforation of a small number of fuel rods in the rotated fuel assembly. As discussed above, any perforations that may result would be localized, there would be only a few perforations, and the perforations would not propagate to other fuel rods or fuel assemblies. The perforation of a small number of fuel rods leads to the release of fission products to the reactor coolant, which are detected by the offgas system. The approximate location of the leaking fuel rods can be determined by flux tilting. A control rod inserted in the vicinity of the leaking fuel rods suppresses the power in the leaking fuel rods, returns the thermal-hydraulic condition to normal heat transfer with its characteristic low temperature difference between the cladding and the coolant, and reduces the fission product release and offgas.

Attachment 3

Design Impact of Rotated Bundle Criteria

Current bundle design criteria requires that the ΔCPR resulting from a rotated bundle analysis not set the CPR operating limit for the bundle. The bundle ΔCPR is derived from taking the maximum bundle delta R-factor between the nominal bundle configuration and the R-factor from the rotated and tilted bundle configuration. The maximum allowable ΔCPR is specified for the core for which the bundle is being designed. The bundle designer translates rotated bundle delta R-factor into a ΔCPR by conservative product line dependent multipliers. The official method of establishing the actual ΔCPR is to run a GETAB calculation with the delta R-factor results from the rotated bundle calculation.

A bundle maximum ΔCPR is usually achieved by reducing enrichments in the three instrument corner rods in a non-uniform gap design. In a uniform gap design, the enrichments are reduced in the three control blade corner rods. The corner and edge rods are the most efficient rods in the bundle. Therefore, reducing the enrichment in these rods and making up the enrichment difference elsewhere reduces the bundle efficiency. Reducing these enrichments also has some impact on thermal margins for high enrichment bundles.

A feature of the BWR/6 designs is a low operating limit CPR, usually around 1.18. This low operating limit requires that the rotated bundle ΔCPR be very low. Consequently, BWR/6 bundles are much more difficult to design. For example, during the design process for a GE10 BWR/6 bundle, it was discovered that in order to comply with the rotated bundle ΔCPR criteria, the nominal R-factors had to be increased because the rotated bundle maximum R-factor could not be made low enough. This results in a degradation of the bundle performance. If the rotated bundle ΔCPR requirement was not a design constraint, this bundle could have a 0.01 to 0.02 better CPR performance from 0.0 exposure through 7 GWd/ST. This CPR improvement is particularly important to BWR/6 plants where the rotated bundle evaluation under current licensing requirements can set the MCPR operating limit.