

Shutdown Configuration Risk Management Guidelines

Color Aggregation and Treatment of Shared Equipment

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EPRI Project Manager

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PRODUCT DESCRIPTION

For many years configuration risk management during low power and shutdown (LPSD) periods has been recognized as an important part of reactor safety. It has also been a research focus of the EPRI Configuration Risk Management Forum (CRMF). Recent research efforts have revealed gaps in the guidance available to the industry to evaluate the overall risk when multiple key safety functions are identified. Additional research has focused on how to address risk assessments involving equipment shared by both a shutdown unit and an operating unit. This report provides methods to address these issues in an effort to develop an industry consensus and contribute to increased LPSD risk assessment standardization.

Background

EPRI CRMF LPSD research in recent years has investigated the reasons for variation and lack of consistency in the risk results represented by color codes. Surveys combined with investigations of methods used at specific plants were used to better understand reported differences. Among the issues identified were the differences in how plants evaluate an overall risk result by aggregating the individual key safety function results, and how plants assess the impact of shared equipment when one plant is shutdown and another is operating. In addition to the issue of the consistency of the color results, there is no available industry guidance on how to address these issues and a variety of approaches are being used.

Objectives

The objectives of this effort were to develop technically sound guidance to:

- Assess the overall risk result aggregated from multiple KSFs.
- Assess the risk of equipment shared between a shutdown unit and an operating unit, addressing the unique considerations involved.

The development of guidance to address these issues will promote a more standardized approach to evaluating risk and provide a sound technical basis for risk assessment practices.

Approach

Following a review of industry shutdown risk assessment practices, various concepts to address development of an overall risk result and shared equipment were explored and provided for comment to the EPRI CRMF Technical Advisory Committee. After review of feedback, specific guidance for each issue was developed.

Results

The proposed guidance recommends using an overall risk result based on the high-level risk metrics of core/fuel damage, support systems, and release protection/containment integrity. This approach is informed by probabilistic risk assessment (PRA)-based monitors that report both core damage frequency (CDF) and large, early-release frequency (LERF). In this case, the use of separate risk metrics for releases and core/fuel damage avoids the error of masking effects in one risk metric by averaging across them. It also has the benefit of distinguishing particular evolutions that might not otherwise be considered noteworthy. The method proposes guidance for plants to average the risk within a risk metric. For example, if decay heat removal and reactivity control were green, but inventory control was yellow, green could be assigned as the

overall color for the core/fuel damage risk metric. In the proposed guidance, an orange or red condition in a key safety function would not be averaged to a lower risk color designation for a high-level risk metric. The method proposed is also flexible, in that it allows for identification and reporting of additional risk metrics, subject to plant needs.

To address risk assessment involving equipment shared between a shutdown unit and an operating unit, the guidance proposes that an additional indicator be added to the risk assessment, such as “other unit impacts.” This would explicitly call out the impact on the operating unit and provide a vehicle for communication between units to ensure that all impacts are explicitly identified. In addition, it would avoid situations that have been observed in the industry, such as when the shutdown unit impact is adjusted to a higher risk level due to the impact on the operating unit, potentially double counting the impact on the operating unit and providing an overly conservative risk assessment for the shutdown unit.

Applications, Value, and Use

This research effort has developed methods for use in shutdown risk assessment programs. Utilities can adopt these practices for implementation at their sites to address the particular issues described in this report. In addition, trial use of these methods can also provide insights. Actual or trial use industry operating experience would provide valuable feedback for this active research area.

Keywords

Defense-in-depth
Low power
LPSD
Maintenance Rule
Risk
Shutdown unit

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INTRODUCTION

Following the publication of NUMARC 91-06 [1] in 1991, formal defense-in-depth assessments of severe accident risk during shutdown conditions became a routine part of nuclear plant operations and safety culture. Over time, the risk evaluation and management processes have evolved, benefitting from the development of qualitative risk analysis techniques and software tools (e.g. for modeling of Defense-in-Depth capability for multiple key safety functions), improved risk management procedures, and the sharing of shutdown operating experience. The issuance of paragraph (a)(4) of the US Maintenance Rule (10CFR50.65) in 2000 formalized the evaluation of configuration risk during at-power and shutdown conditions, with the shutdown evaluations using industry guidance documented in NUMARC 93-01 [Reference 2].

EPRI has previously developed guidance for the development of qualitative risk models [Reference 3]. In 2011, the EPRI Configuration Risk Management Forum (CRMF) performed a benchmarking survey of US and international utilities concerning configuration risk management practices for both at-power maintenance and shutdown maintenance [Reference 4]. This survey confirmed that US plants were utilizing sophisticated approaches to evaluate shutdown risk and were generally employing similar methods to evaluate the defense in depth available for each key safety function (KSF). These methods are used to assign “risk colors” (typically, “green”, “yellow”, “orange”, and “red”) to each KSF and to the overall status at each point during a refueling outage. However, the survey also showed that despite the apparently similar approaches in use, there was a significant variation in the typical risk colors calculated during outages at seemingly similar plants.

The CRMF performed further investigation into the possible causes of the variations in KSF risk colors [References 5 and 6]. An additional survey was performed to obtain more detailed information and further investigations were conducted with several plants that participated in the follow-up survey. Through the data collected, it was recognized that several factors may be causing some of the observed variation. These factors are:

- Differences in how plants aggregate the individual risk colors for each KSF into an overall outage risk color
- Differences in how the risk impacts of outages of portions of shared systems in a multi-unit site are assessed for the outage unit as well as the at-power unit
- Differences in how risk colors are assigned for KSFs in which there may be limited defense in depth available, as well as how High Risk Evolution (HRE) adjustment factors are applied in various plant configurations
- Differences in the specific methods used to evaluate shutdown risk, as well as differences in methods used to perform pre-outage risk evaluations and daily risk evaluations during the outage
- Differences between otherwise similar plants concerning the imposition of various “programmatic aspects” or other management directives concerning allowable levels of risk, restrictions against entering various configuration, etc.

Industry guidance concerning these specific factors was not found in the available industry literature. Therefore, the CRMF is developing guidance that can be used by nuclear plants to help provide greater effectiveness, standardization and consistency in shutdown risk management.

This Technical Update report presents such guidance for two of the above five issues: the aggregation of individual KSF risk colors, and the treatment of inter-unit impacts due to shared systems. The CRMF is considering possible approaches and guidance to address the remaining issues for publication in subsequent reports.

It should be emphasized that these guidelines should not be considered to impose any regulatory requirements or to be considered as a performance metric for a particular plant site as program elements and implementation details can vary widely. The purpose of this guidance is to identify important technical considerations and help promote consistency in assigning KSF and overall outage risk colors in the treatment of specific configurations.

2

AGGREGATION OF KEY SAFETY FUNCTION COLORS

Overview of the Issue

As recommended by NUMARC 91-06, shutdown risk is typically assessed based on the status of the defense in depth (DID) provided for each Key Safety Function (KSF). The KSFs recommended in the NUMARC document include Reactivity Control, Decay Heat Removal, Inventory Control, Containment Integrity, and Electric Power Availability. Many plants have expanded the scope of the KSFs beyond NUMARC 91-06 to address the availability of other support systems, such as cooling water. Other KSFs may also be added, such as those that pertain to the Spent Fuel Pool (i.e., Decay Heat Removal and Inventory Control). In addition, some plants have created “pseudo KSFs” to monitor additional items, such as compliance with Technical Specifications for certain situations, for monitoring the impacts of outage activities on another operating unit at the site, for monitoring of plant-specific administrative requirements, or for other purposes.

The evaluation of each KSF as plant configuration changes occur throughout the outage typically results in a “risk color” assignment for each KSF, ranging from “green” to “red”. The assignment of these risk colors is based upon the degree of defense in depth that is available to support each KSF. At any given point in the outage, the risk colors will vary for each function. To assist in communicating outage risk to plant personnel, it is convenient to assign an overall “outage color” based on review of all of the individual KSF risk colors for each unique plant configuration. However, there is no industry standard for how to perform such an aggregation of the KSF risk colors and several methods are currently used by the industry.

Review of Current Approaches

Among the aggregation methods that are in use in the industry are the following:

- The highest risk color indicated for any KSF within a given time period of the outage is assigned as the overall outage risk color for that time period
- An average of all of the individual KSFs is used to determine the overall outage risk color for a given time period
- A weighting formula is used to combine the individual KSF risk colors into an overall risk color for a given time period (i.e., some KSFs have a greater impact on the overall color determination than others)
- The individual KSF colors are reported individually, and there is no attempt to develop an overall outage risk color.

Two plants with the same individual KSF risk colors could report different overall outage risk colors if their aggregation methods differ. For example, if all but one of the KSFs evaluate as “green”, with the other KSF evaluating as “yellow”, a plant that assigns the highest risk color would determine the overall outage color to be “yellow”. However, a plant that computed an “average” or “weighted average” outage color would probably assign the overall outage risk color to be “green”. Comparing the risk profiles of these two plants based on the overall outage risk color metric would imply one plant’s outage had a lower risk than the other; however, this conclusion would be incorrect.

The assignment of the highest KSF risk color as the overall outage color is a conservative approach. In the example described above, having only one KSF at a “greater than green” level will bias the outage risk color to a “greater than green” level as well. Having a conservative assessment is generally considered a safe approach and is consistent with many other design and operational practices used in the industry. On the other hand, “risk evaluations” are usually performed on a best estimate basis so that actual risks are not overshadowed by conservative assumptions.

The process of computing an “average” color or a “weighted average” color lacks a standardized approach for doing so. There are several factors to consider that could lead to variations in how the average may be calculated at different plants:

- As the number of specific KSFs evaluated at each plant may vary, and average at one plant might consider only five KSFs, while the average at another plant might consider seven or eight KSFs. The differences in number of KSFs included in the average can lead to different ‘average’ risk color results.
- It can be argued that certain KSFs may overlap in functionality with other KSFs. For example, common systems may support both the Inventory Control and Decay Heat Removal KSFs. An equipment outage that impacts the Support System Availability KSFs would also most likely impact one or more of the other ‘front line’ KSFs, so there is some measure of double-counting of this risk impact. The evaluation of support system availability KSFs can be very helpful for identifying risk-significant outage activities and is encouraged; however, including them directly into a calculation of overall “outage risk color” may not be appropriate.
- The Containment Integrity KSF is a surrogate for radioactive release risk, while most of the other KSFs are surrogates for core/fuel damage risk. Including them both in a single “average” calculation, or equating them equally in the color aggregation process might be inappropriate since a different risk metric is being considered in the Containment Integrity KSF.

If additional “pseudo KSFs” are defined to monitor other functions and plant conditions, these probably should not be included in any aggregated risk color measure. The bases for the risk colors that are defined for the “pseudo KSFs” are probably different from those used for the primary KSFs (e.g., Tech Spec compliance). Therefore, blending them into the overall risk color calculation may skew the results inappropriately.

Several plants are using quantitative shutdown risk models; however, the vast majority of US plants are using qualitative DID models. The quantitative models use core/fuel damage as the primary metric, which places primary emphasis on the Decay Heat Removal and Inventory

Control KSFs. Support System Availability is considered quantitatively within the models for the above two functions. Reactivity Control is considered within the quantitative models to some degree; however, reactivity control impacts are generally not shown to be significant contributors in the quantitative models. Containment Integrity is not specifically addressed, unless the models also include a Large Release metric. In lieu of a quantitative model for the containment, a separate qualitative DID model may be used for Containment Integrity. For the spent fuel pool, pool boiling is often used as the surrogate metric for fuel damage. These models primarily consider decay heat removal, but inventory makeup may also be considered.

Proposed Guidance

The modeling approach used by quantitative risk monitoring models provides an instructive precedent to inform an approach for grouping (and possible weighting) of the qualitative KSF evaluations. First, as Containment Integrity is primarily a release prevention function, it may be appropriate to record the status of this KSF separately. This is similar to the process by which core damage frequency and large early release frequency are reported separately for quantitative at-power CRM evaluations.

Reactor core and spent fuel pool functions can also be separated for overall reporting purposes, as the systems used to protect fuel in the reactor and the fuel pool are separate (but may share common support systems).

Under such an approach, the aggregated overall outage risk assessment results could be reported as two or three distinct “risk colors”: Core/Fuel Protection and Release Prevention.

Core Protection and Spent Fuel Protection could be reported separately, or combined into a single metric. As some plants track only spent fuel pool heat removal as a KSF for the pool, this function could be considered on an equal basis with the other front-line core protection functions (decay heat removal, inventory control and reactivity control) in an overall Core/Pool Protection metric. Any additional “pseudo KSFs” would then also be reported separately.

In addition, NUMARC 91-06 considers Power Availability to be a frontline KSF. For support systems, two considerations are important. One is the consistency between the response of the support system and the front-line systems. For example, if Power Availability is evaluated as orange and all of the other KSFs are yellow, the consistency of the model is questionable. The other consideration is that double-counting can result. If the front-line system is yellow because of a support system, then this should not provide a more severe overall outage risk assessment result. In any method to aggregate the risk metrics for defense-in-depth risk assessments, focusing on the reactor safety insights is of paramount importance. Accordingly, a support system outage metric is also an appropriate category to report as a separate risk color. Aggregation of the functions that make up each top-level risk color metric are shown in Table 2-1.

**Table 2-1
Possible KSF Aggregation Methods**

High-Level Outage Risk Metric	KSFs to be Considered	Aggregation Methods
Core / Fuel Protection	Decay Heat Removal Inventory Control Reactivity Control Support System Availability SFP Heat Removal SFP Inventory Control Support System Availability	Approaches to aggregate core/fuel protection could include: <ul style="list-style-type: none"> • Assign highest risk color from any KSF • Aggregate the risk color of all KSFs as described below. • Place primary weighting on front line functions (decay heat removal, inventory control, reactivity control, SFP heat removal and SFP inventory control) • Alternatively, SFP Fuel Protection could be designated as a separate outage risk metric.
Support Systems	Power Availability	Approaches to include support systems could include: <ul style="list-style-type: none"> • Reporting the Power Availability KSF result. Power Availability is a KSF according to NUMARC 91-06 and includes AC power, instrumentation and control power, and switchyard/transformer yard and electrical equipment activities (e.g., transformer or transmission line work). • Cooling water is not a KSF per NUMARC 91-06, but may be monitored by individual plant models. Its status should be available as part of the assessment, but should not be used to diminish the Power Availability result.
Release Prevention	Containment Integrity	No aggregation needed – single KSF

Based on the evaluation of the various approaches currently in use in the nuclear industry as discussed and analyzed above, the following guidance is proposed for the aggregation of risk colors for shutdown risk evaluations:

- The Containment Integrity KSF risk color should be reported as the Release Prevention high-level risk metric separately from the other monitored KSFs when aggregating an overall risk color (i.e., report a fuel damage risk color and a separate radioactive release risk color). This approach also provides better consistency between the at-power and shutdown risk color assignment processes.
- The Support Systems risk metric, which would normally represent the Power Availability KSF, should be reported separately from the other monitored KSFs when aggregating an overall risk color. This would eliminate double-counting when a front-line KSF is in an elevated color state due to a power availability issue and call particular attention to evolutions involving AC power, DC power, or switchyard activities.
- With the Support Systems risk metric reported separately, the “average” risk color calculation for Core/Fuel damage risk metric can focus on the frontline KSFs (i.e., Reactivity Control, Decay Heat Removal, Inventory Control).
- The following approach for averaging the risk of the individual KSF colors within a risk metric is recommended. It is expected that this would primarily apply to the Core/Fuel damage risk metric, but could be expanded more broadly.
 - Orange or Red results should not be reduced in the overall evaluation. For example, if any one of the front-line KSFs in the core/fuel damage metric is orange or red, this should be the aggregated color for the Core/Fuel Damage risk metric.
 - Within the higher level risk metric of Core/Fuel Damage, a yellow result in one KSF can be averaged to an overall green result if at least two other KSFs are green.
 - For other combinations, the majority rules. For example, two yellow KSFs average to green if there are at least 3 additional green KSFs.
 - A plant may take exception to the above guidance and choose the more severe color in response to the plant conditions or HREs. Nuclear safety is the highest consideration.
- Additional plant-specific “pseudo KSFs” (i.e., those not defined in NUMARC 91-06) that may be defined to monitor certain plant conditions and configurations should have their “risk colors” reported separately from the main outage risk color aggregate measure(s). The use of such “pseudo KSFs” is encouraged, as they can provide additional risk management insights for plant-specific situations.

If the above guidance is utilized, the use of the multiple metrics would communicate a thorough understanding of the outage risks. While not necessary, if a plant desired a single color selection, choosing the highest risk color among the higher level risk metrics of Core/Fuel damage, Release Prevention/Containment Integrity, and Support Systems should provide a good indication of the outage risk status at each point in the outage.

Separate reporting of Spent Fuel Pool status as a higher-level risk metric and any plant-specific “pseudo KSFs” as additional risk measures can also be used, based on plant preferences. Other related KSFs or “pseudo KSFs” can be combined into a related higher-level risk metric using the approach outlined above as needed by each plant.

Conclusions

The proposed guidance provided above should help to provide greater standardization of how an overall “outage risk color” can be evaluated. the guidance also improves consistency between how a qualitative shutdown evaluation would be reported as compared to the at-power quantitative risk evaluations by segregating the release prevention/containment integrity risk metric from core/fuel damage.this proposed approach would replace a single “outage color” with a minimum of three higher-level risk metrics, core/fuel damage, containment integrity, and support systems. the approach includes guidance on how to assess an overall color within each risk metric and provides the flexibility to allow for expansion depending on plant needs to include other possible indicators or risk metrics.

3

MODELING OF INTER-UNIT IMPACTS OF OUTAGE ACTIVITIES

Overview of the Issue

Nuclear power plants that are part of a multi-unit station may share various plant systems. When one unit is in a refueling outage, maintenance activities or alternate operating alignments may impact portions of these shared systems. The outage activities may have an impact on one or more of the shutdown unit's Key Safety Functions (KSFs). In addition, the maintenance may also have an impact on the risk profile of the other (most likely operating) unit. The issue concerns how to best model the impacts of such maintenance on each unit in a multi-unit station, and how to allocate that risk between the Configuration Risk Management (CRM) evaluations of each unit.

Review of Current Approaches

There is no common approach to the treatment of inter-unit impacts in shutdown CRM evaluations. However, some plants have developed specific KSFs to monitor the status of shared systems and cross-tied systems as part of the shutdown CRM assessment. As a minimum, these KSFs consider the availability of the shared/cross-tied system to support a given shutdown unit. However, a subset of plants also attempt to consider the impact of the shared/cross-tied systems unavailability on the *other* units of the station within the risk assessment for the shutdown unit. This latter approach can lead to double-counting of the risk impacts, as the shutdown unit's "risk color" for this KSF would be increased as a result of expected impacts on the other unit(s). However, the CRM evaluations for the other unit(s) should separately evaluate the risk impact of the shared/cross-tied system's unavailability..

Discussion of the Issue

Due to differences in individual station designs, the extent of these impacts can vary from very minimal impacts to more significant ones as systems that are either shared with an operating unit or are credited by the operating unit's PRA model as a credible backup system (e.g., cross-tying of emergency diesel generators or cooling water systems) are removed from service due to outage activities.

Shared systems in a multi-unit station could be impacted by outage activities in various ways, including the following:

- Removal of one or more key components in a train of the shared system; most of the shared system may remain functional for all units of the station. However, prior to crediting an impaired system in this manner, the analyst must ensure that the shared system can, in fact, support multiple units with portions out of service.
- Complete removal of the portion of the system associated with the shutdown unit; the operating unit(s) rely only on those portions of the shared system not associated with the shutdown unit.
- The shared system is placed into an off-normal alignment in order to support activities on the shutdown unit; some or all of the shared system functionality remains functional for all units of the station.
- Removal of some or all of the shared system results in this system being unavailable to support the other units of the station.

For an operating unit, the crediting of a cross-tie to systems in the shutdown unit needs to ensure that the credited systems in the shutdown unit remain available. For example, cross-ties of emergency diesel generators may be credited in the risk model; however, one diesel generator may be out of service in the shutdown unit for maintenance or testing. As noted above, an outage activity that impacts a shared system in a multi-unit plant can have a risk impact on multiple units. Certainly, the risk impact of the outage activity on the unit undergoing the outage should be associated with that unit. In some cases, an activity on a shared system might not have an impact on the other unit(s) in a station, if that shared system is not needed to support any of the available systems/trains credited to meet a KSF. For example, if a train of a frontline decay heat removal system is already out of service in the other unit(s), then removing a train of a shared system that supports the out-of-service train would have no additional risk impact. This would be more likely to occur during a multi-unit outage.

The impact of the outage activities on the other unit(s) of the station would most likely be a risk increase of some type, since the other unit(s) can no longer credit all of the capabilities of the shared system. Because the Maintenance Rule requires that all plant configuration changes be evaluated for risk impact, the CRM evaluation of the shared system impact on the remaining unit(s) of the site will be directly reflected in those units' risk evaluations. For an operating unit, this impact would be evaluated quantitatively using a PRA-based model. If the other unit(s) were shut down, then the impact would most likely be evaluated using a qualitative model.

Proposed Guidance

To indicate to the outage schedulers that an activity on a shared/cross-tied system could have an adverse impact on other unit(s) at the station, it is appropriate to provide some indication of that impact in the shutdown unit's KSF evaluation. However, to raise the "risk color" of an existing KSF (e.g., for support system availability) to show the impacts on other units in effect, results in double-counting of the risk impact on the other unit(s), since the shared system impact is already

being considered in the CRM evaluations for the other unit(s). Assigning a “risk color” increase to the shutdown unit may result in a conservative over-estimation of the risk impact to the other unit(s). The specific CRM evaluations for the other unit(s) will provide a more realistic assessment of the risk impact.

An alternative approach would be to define an additional function for evaluation (e.g., named “Other Unit Impacts”) that could be used to alert the outage scheduler of the potential impacts on another unit in the station when shared systems are being worked on or re-aligned. The risk color from this new function would NOT be included into the overall risk color evaluation for the outage. However, the presence of an elevated color status for this function would be used to flag that a specific CRM evaluation needs to be performed (by the other unit(s) in the station) during the outage schedule development process to ensure that the risk impacts are acceptable. During the outage itself, the presence of an elevated risk color for the additional function would also be used to alert outage personnel of the impacts of the shared system work activities on the other unit(s) in the station.

Conclusions

In situations in which outage activities can impact a shared system in a multi-unit station, the risk impacts on all affected units must be considered. However, these risk impacts must be properly allocated to each affected unit. The “risk color” calculated for KSFs for the outage unit should NOT include the risk impacts of shared system activities on other units. However, it is recommended that all outage activities that affect a shared system be flagged or identified (e.g., by the use of a separate shared system impact indicator) so that the potential risk impacts on the other unit(s) in the station can be evaluated for acceptability during the outage schedule development process. If the risk to the other unit(s) is acceptable, then the planned activity on the shared system can be performed. During the outage, the shared system indicator can also be used to alert station personnel of the specific time periods during which shared system activities are underway (e.g., for daily outage review meetings, pre-job briefings, etc.).

4

CONCLUSIONS AND NEXT STEPS

The Shutdown CRM Guidelines presented in this report represent a first step in the development of practical guidance that can be used by plants in the implementation of their shutdown CRM programs. Having better standardization of each plant's shutdown CRM processes can better enable sister plants to compare risk results for benchmarking purposes. This, in turn, can also help to improve risk management practices through the benchmarking process.

The first two technical areas considered, risk color aggregation and the treatment of inter-unit risk impacts, were selected for development because they can help to improve the standardization of how outage "risk colors" are determined without a significant change in how each plant's current CRM program is structured. The risk color aggregation guidance primarily impacts how each plant might aggregate its individual KSF evaluations to produce overall risk color results. The treatment of inter-unit impacts guidelines provide a consistent approach to addressing this issue. The guidance may impact individual plants to varying degrees, depending upon the extent of shared/cross-tied systems of concern, and how these systems are currently considered in the shutdown CRM process.

The proposed guidance is published for industry review and comment in this active research area. Industry feedback and possible implementation of the proposed approaches on a trial basis can also help to provide valuable insights for the industry.

5

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