MSPI DRIVEN SAFER NUCLEAR POWER PLANT – CALLAWAY ENERGY CENTER

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MSPI (Mitigating System Performance Index) is one of important performance indices of NRC Reactor Oversight Process. In order to improve MSPI performance and gain additional margin, Callaway Energy Center had installed AEPS (Auxiliary Emergency Power System) and a Non-Safety Motor-Driven Auxiliary Feedwater Pump (NSAFP). Both modifications were completed in 2011 before the Japan Fukushima Daiichi nuclear accident. This risk-informed decision making exhibited that Callaway Energy Center had incorporated nuclear safety principles into their plant operation and taken proactive actions to keep continuous improvement for being a safer plant.

This paper introduces lessons learned from the MSPI-Driven project from a PRA perspective. Furthermore, insights gained by the author with respect to MSPI, its' purpose and definition, and how it can be optimized to support nuclear safety are discussed. Herein, to aid in the optimization effort, the MSPI Analyzer software has been developed. The resultant MSPI information can be used to select the better plant modification design, and to determine the entire GREEN margin combinations in advance once the PRA model and plant operational data are defined

Key words: **PRA, MSPI Analyzer, Risk Worth, Operation Optimization, Safety, Risk-Informed Decision**

I. INSTRUCTION

MSPI (Mitigating System Performance Index) is an important performance index that is used in the NRC Reactor Oversight Process for assessing licensee performance. It compares the plant operation statistics with the industry and plant-specific performance baselines in order to determine mitigating system performance of the plant, which is characterized by a color band. For risk characterizations greater than green, the respective regulatory response will follow in accordance with the action metrics.

With respect to the predefined baselines, MSPI reflects implicitly or explicitly the as-built, as-operated, as-maintained and as-planned plant. From author's experience, MSPI is not only a performance index of plant operation but also an index that can be used to compare the different modification designs in the plant and provide insights to improve plant safety. Furthermore, given the acceptable threshold (1.0E-6, Green-White threshold), PRA parameters and the plant actual or estimated operational data, all marginal green combinations can be determined in advance so that it provides the potential MSPI optimization for plant operation, work management, engineering and maintenance to plan, schedule and execute the work in an integrated way. This means the MSPI goals based on all the possible MSPI margin combinations can be pre-determined once the PRA and plant operational data are known.

In this paper, section 2 explains MSPI from the pattern recognition perspective, section 3 is a case study of the MSPI application at Callaway Energy Center and the insights gain from the project, and section 4 introduces how MSPI is optimized for better plant performance, and section 5 provides the conclusion.

II. WHAT IS MSPI

It is widely recognized that MSPI is the sum of Unavailability Index (UAI) and Unreliability Index (URI). From regulatory guide guidance NUREG-1816 (Ref. 1), the MSPI is defined mathematically as:

$$MSPI = UAI + URI \qquad (1)$$

The following represents an understanding of the author about the MSPI program and its applications. From the author's perspective, MSPI is not simply a sum of UAI and URI but a comprehensive and integrated indication of how effective the mitigating systems are in terms of plant design, maintenance and operation. If MSPI in equation (1) is viewed as a Numeric Index (NI), then overall the MSPI is constituted of NI (the sum of UAI and URI), the risk cap (RiskCap) and the Performance Limit Exceed (PLE).

$$MSPI' = \begin{cases} NI \\ RiskCap \\ PLE \end{cases} \qquad (2)$$

Where: $NI = UAI + URI$;

In order to understand the MSPI program better let's review MSPI from another angle: the pattern recognition, which is the capability of our daily intelligence. Normally in order to identify the potential pattern or diagnose an issue of a subject, it is necessary to identify a few features of the subject as an indication of certain patterns and establish criteria against which a decision will be made. This indication can be a numerical definition of certain property of the subject in the form of an index or a group of indices, and the decision will be made based on the numeric index and the given criteria. The decision made may or may not match the actual or true case in reality. So in order to evaluate how good a decision is, a pair of parameters is defined as (T/F, T/F); each can be either True or False. The first parameter indicates the state of the existence of the pattern or issue, this is a decision based on the features against the criteria; while the second parameter is the actual state of the reality, which could the best judgment according to the best knowledge and experience for some cases where such actual state or condition is not obvious. A recognition table or truth table can be used to identify how accurate a decision made for a pattern or an issue of interest is.

TABLE I. Truth Table of Recognition

Actual State / Indication State	True	False
True	(T, T)	(T, F)
False	(F, T)	(F, F)

The pairs (T, T) and (F, F) are correct determinations using the index, where the indication shows the pattern or issue exists (T) or not (F), the real pattern or issue indeed exists (T) or not (F) in reality. On the other hand, the pairs (T, F) and (F, T) represent an incorrect determination, where the decision does not match the real situation. Taking land mine detection as an example, in order to find a path though a minefield, a solider uses some technology to provide an index, based on which he will flag the spot to indicate there is a land mine (T) and or not (F). The prefect detection is expected as all cases being (T, T) or (F, F) pairs which means all places are correctly flagged. But in reality, mine detection is not perfect, so there may exist incorrect detections: (T, F) and (F, T). There are some decisions made by the solider whether a mine exists or not, but the reality is the opposite. The consequence of the incorrect detections is quite different. These incorrect decisions (T, F) and (F, T) should be minimized based on its consequence or cost in order to achieve the maximum correct decisions (T, T) and (F, F).

Therefore, in terms of the MSPI acceptance criterion for green or acceptable risk, i.e. ≤ 1.0E-6, if using equation (1) only, for very high risk significant system, one failure may render the numerical index (NI) above 1.0E-6. This actually could be a system design issue since the risk associated with one failure of the system is simply too high. As it is recognized that no system is perfect, a random failure may occur at any time during the plant operation. Thus, RiskCap can be applied to accept one highest risk significant system failure by capping its risk to 5.0E-07 given the total MSPI being less than or equal to 1.0E-5 (below Yellow). According to industry guidance NEI 99-02 (Ref. 2), RiskCap is applied to treat the statistical fluctuation. On the other hand, the NI could be far less than 1.0E-6 even if there are more failures than realistic for the low risk significant mitigating systems. The maximum is limited by applying the PLE; therefore, the MSPI determination can be summarized as indicated in Table II:

TABLE II. Overall View of MSPI

MSPI / NI	Non-Green (True)	Green (False)
Non-Green (True)	(NI=T, MSPI=T)	(NI=T, MSPI=F) & RiskCap
Green (False)	(NI=F, MSPI=T) & PLE	(NI=F, MSPI=F)

This means the RiskCap is invoked to address the (T, F) of the potential zero-margin case for the very high risk significant component group but less than a Yellow characterization for a mitigating system, while PLE is invoked to deal with the (F, T) of an excessive margin case for the very low risk significant component group of a mitigating system. The RiskCap and PLE are applied only to URI. RiskCap removes the excessive risk above 5.0E-7. The invocation of the RiskCap suggests that potential deficiencies or weaknesses exist in the mitigating system in design or operation. Additionally, unavailability (UA) hours normally are low risk significant, UAI reflects the risk of the unavailable time linearly and the total UA hours should be less than some threshold below 36 months (3*8760 = 26280 hours)

III. MSPI APPLICATION: A CASE STUDY

In 2010, Callaway Nuclear Power Plant experienced a white performance index for an Emergency AC Power system and a potential white index in Heat Removal System – AFW (Auxiliary Feed Water). Temporary Diesel Generators were installed in order to provide the temporary backup emergency AC power to improve the MSPI and reduce the plant risk. At the same time potential plant modifications were explored in order to gain the EAC (Emergency AC) and HRS (Heat Removal System) MSPI margin and reduce plant risk permanently. Based on the preliminary MSPI margin study, the plant management decided to spend millions of dollars to install the Alternate Emergency Power System (AEPS) and motor-driven Non-Safety Auxiliary Feedwater Pump (NSAFP) for better MSPI performance and safer plant. The modifications were completed in 2011, MSPI margins were restored, and the plant Core Damage Frequency (CDF) was reduced to about half. This plant upgrade was originally initiated due to low MSPI margin and was completed before the Japanese Fukushima Daiichi nuclear disaster, which revealed the critical importance of the EAC and the wisdom of the decision.

This MSPI driven project for Callaway Energy Center is an example that MSPI program can encourage plant management to take proactive actions to improve MSPI margin and improve nuclear safety by providing additional means for Emergency AC power and decay heat removal in response to internal or external events including beyond design basis events. This is one factor that supported Callaway Energy Center earning an INPO 1 “excellent” rating for its overall performance when many single units were trending down. This exemplary case shows that better a MSPI program can improve plant safety.

The installation and operation of AEPS and NSAFP have been modeled in PRA and evaluated qualitatively and quantitatively in terms of MSPI, Defense-in-Depth and safety margin. The insights of PRA analysis had been incorporated into the engineering design. The following sections discuss highlights and lessons learned from these risk-informed design modifications.

III.A. Power Source Design

At first, potential AC power sources were compared: large combustion turbine generator, large diesel generators, and small diesel generators. The decision was made to go with the small diesel generators as they were judged to be the best option in terms of reliability and cost efficiency. Taking into consideration diversity, redundancy and independency of the power source, the normal power supply of AEPS is a power line from another grid with a set of four small diesel generators (2MW) as its backup power.

Upon request, or in the event of a Station Blackout (SBO), AEPS will manually feed one train of the safety related class 1E bus through a dedicated transformer other than through the plant switchyard. The switchyard is bypassed because of the consideration of its availability in the event of the Loss of Offsite Power (LOOP). The operator can crosstie the safety-related buses if necessary. Taking into account external events such as tornadoes and high winds, the power lines are buried underground and its route is also evaluated qualitatively.

In the Fukushima Daiichi accident, the plant performed as designed when the earthquake and significant aftershocks occurred, including the emergency AC (EAC) sources supplying the safety-related loads. However, the seismic-induced tsunami that resulted some time later resulted in unavailability of the EAC sources which subsequently lead to core-damage at three of the units. This accident shows the critical importance of emergency power during an event far more severe than the design basis. A sister plant of Callaway had built a similar remote diesel-generator farm away from the site as a supply of backup AC power; however it fed the safety related bus via the switchyard. In 2012, a loss of offsite event occurred at this plant, EDGs started as designed but it would be difficult to credit those near site diesel generators to provide AC power due to loss of the switchyard. This event reveals that a loss of the common system (the switchyard) could prevent the extra AC power source from providing the emergency power when needed, thus there would be no improvement as expected and defense-in-depth would not be realized in an event that would cause a loss of switchyard. The above lessons show that AEPS at Callaway, which was driven by MSPI margin, is a visionary modification for a more robust and safer plant.

III.B. Extra Decay Heat Removal Design

The Turbine Driven Auxiliary Feed Pump (TDAFP) is high risk significant equipment because of its safety function to remove decay heat through Steam Generators, especially in the event of an SBO. A Non-Safety Auxiliary Feed Pump (NSAFP) powered by the AEPS had been installed to backup the TDAFP when required. The NSAFP was installed in the basement of Turbine Building. Later it was identified that the secondary stream line break could potential fail the operation of the NSAFP, consequently NSAFP could not be credited in such event without further analysis. Thus without the backup of NSAFP as additional means to remove decay heat, one TDAFP fail to run margin was lost. The lesson learned is that the MSPI results can be tweaked to compare the different design options in detail by correctly identifying comprehensive interactions among the initiating events, equipment physical locations, and the system functions.

III.C. Observations and Areas for Improvement

During the period of the project, the author identified a few areas that should be considered for the improvement of the MSPI program.

(1) It is time consuming to input data using the current regulatory MSPI website for the design comparison. One set of data for all MSPI systems could take two engineers two hours. If there are tens of cases for design comparison, the time needed could be substantial. Let alone the website has down-time.
(2) Only integer margins are given. A small improvement in the index cannot be measured in MSPI.
(3) Only the maximum margin presented in terms of unavailability hours, numbers of demand failures or numbers of runtime failures can be determined.
(4) The green-white threshold uses the 1.05E-6 as threshold other than 1.0E-6.
(5) Excessively high UA hours may not be appropriate. The total UA hours should be capped by some threshold below 26280 hours (36 months).
(6) Shorter EDGs mission times can lead to additional EAC system fail to run margin.
(7) Without procedural or physical improvement of the plant, gaining the margin for one mitigating system through the PRA manipulation to remove conservatism is very likely to cause the loss of margin for another system.
(8) There is a balance between the removal of low risk significant (≤1.0E-6) components for less failures and the addition of such components for more demands.

The software, MSPI Analyzer, has been developed with the above consideration for MSPI application and optimization. This tool can save significant time and resource requirements by quickly inputting and calculating multiple cases of multiple plants simultaneously. It measures the MSPI in real numbers other than integer, for example, the demand margin is 3.99 with the auto-start AEPS design, but 3.01 with the manual start design. It shows that the auto-start design is better than manual start and some improvement could achieve a demand margin of 4.0. If integer is used, margin is 3 for both designs. The potential improvement opportunity may be missed because the difference in margin between two designs cannot be shown. In addition, MSPI threshold is 1.0E-6, while the widely used online tool gives 5% more margin. Operating the plant at the mercy of the 5% margin or influenced by rounding error shows that the safety margin principle is barely maintained. As a matter of fact, if the digit of input coefficient is carefully selected and the algorithm is well designed for the digital computer, the round off error of every step of the MSPI calculation can be determined. The total rounding error of the MSPI calculation could be calculated and then the threshold could use 1.0E-6; therefore, the 5% margin may not be necessary.

IV. MSPI OPTIMIZATION

Overall, MSPI is a comprehensive mitigating systems index taking into account risk and operational factors with respect to PRA modeling, plant operation, design and maintenance, implicitly or explicitly.

Currently MSPI margin reports of mitigating systems only present maximum available margin in terms of unavailability hours for the system trains, or unreliability failures for component groups. Most of the time, a plant responds passively and takes action only when the margin is low and close to the green-white threshold of a mitigating system. Is it possible to find all possible green margin combinations in advance, and then given the identified green margins take pre-defined management actions proactively in order to improve the MSPI program? The answer is YES. This is another way to practice MSPI margin management. Typically, the margin is tracked in terms of the calculated small MSPI values and the maximum available hours or failures. With all the green combinations available for each individual mitigating system, the plant can track and manage the MSPI in a new way, in which the uncountable MSPI margin can be converted into the potential paths linking the countable green combinations by comparing the plant actual operation hours and failures against the available green combinations. Pre-defining all green MSPI margin paths can promote clear communication regarding MSPI across the plant and facilitate the understanding of MSPI margins and potential plant improvements for plant staff having little PRA or MSPI knowledge.

Frequency (CDF and LERF) and Probability (CCDP and CLERP) are the risk metrics used in risk assessment and risk-informed applications for nuclear power plants. The frequency and the number of events are normally countable or measurable but the probability is not. However, probability can be calculated based on some risk modeling and assumptions. MSPI is a function that relates the plant risk CDF linearly with the unavailability hours and the numbers of unreliability failures with the aid of the coefficients Xs named “RISK WORTH”, which measures the risk increase in terms of CDF or MSPI change from one unavailability hour or one unreliability failure. This concept can also be applied to calculate the Maintenance Rule (MR) performance criteria and identify the potential initiators or incidents of equipment or human performance that could result in a Significance Determination Process (SDP) evaluation.

An algorithm to address this problem to achieve operational optimization was derived, and accordingly a software tool, MSPI analyzer ®, has been developed to implement the idea. The software provides many features in order to find better solutions or design for achieving MSPI program excellence (Ref. 3). Solving the equation (3) below by traversing the integer unreliability failure space and assigning the unavailability time for the residual margin, one can determine the possible green margin combinations, which can be used as the MSPI operation goals.

$$\begin{cases} MSPI = \sum_i X_i^{UA} * T_i + \sum_j X_j^{UR} * N_j \leq 1E-6 \\ Subject\ to: \\ \qquad N_j < N_j^{max} \\ \qquad PLE \\ \qquad Risk\ Cap \end{cases} \quad (3)$$

Solving this equation presents an optimization problem with respect to searching and determining the unavailability hours for train *i* in the real numbers and the unreliability failures for component group *j* in integer numbers. For each mitigating system, the Nmax can be defined first; then search all the Ns and Ts with fixed N and variable T to meet the threshold of 1.0E-6 that needs to be adjusted in the application.

With the inputs same as that for the current MSPI program, running the MSPI analyzer provides an objective function for each system. The maximum unreliability failure for a single component group of a mitigating system can be easily calculated based on the available margin and its risk worth, thereafter the unreliability failures not exceeding its maximum for the individual component group are combined for all the component groups in that mitigating system. Such combinations span the search space for possible unreliability failure green combinations, thereafter the residual margin will be assigned to unavailability hours. Mathematically, this is an optimization problem to maximize the objective function subject to the limitations of the real and integer values.

Thus, given PRA (Probabilistic Risk Assessment) parameters like CDF, FV (Fussell-Vesely Importance), CCF (Common Cause Factors), operational data such as critical hours, estimated or actual component run time and demands and industry and plant specific baseline values, the MSPI operational goals can be determined by generating the objective functions that are used to define all the possible green combinations, so that the acceptable operational profile for the mitigating systems can be developed in advance and the plant can manage MSPI margin trending in an integrated way and have the insights and information to make MSPI a risk-informed decision.

Table 3 shows a demo example of the Emergency AC Power System, where the Xs of (A) and (B) are the unavailability risk worth for the trains A and B, Xs of (C), Xl of (D) and Xr of (E) are the unreliability risk worth of the demand, load run and run of diesel generators. The asterisks indicate the unreliability risk worth is greater than 5.0E-7 and potential invocation of the RiskCap. The adjusted green-white threshold is 3.362E-06.

TABLE III. Train Unavailability and Component Group Unreliability Risk Worth

	(A) TRNA.X	(B) TRNB.X	(C) * DG.Xs	(D) * DG.Xl	(E) * DG.Xr
X	1.534E-09	1.534E-09	6.639E-07	6.528E-07	2.593E-06

Then the corresponding object function is

1.534E-09*A +1.534E-09*B + 6.639E-07*C + 6.528E-07*D + 2.593E-06*E <= 3.362E-06

Subject to the RiskCap, Performance Limit Exceeded (PLE), all the unavailable hours and unreliability failures have to meet the equation above, where A and B are unavailability hours and C, D, and E are failure numbers. All the green conditions are boiled down to meet one equation, which is an integer and real number optimization problem. With the extra margin from the RiskCap, the maximum Fail to Start (FTS) margin is 5, the Fail to Load/Run (FTL) margin is 5, and the Fail to Run (FTR) margin is 2, so the object function subjects to $C \leq 5$, $D \leq 5$, and $E \leq 2$.

The total possible failure combinations are 6*6*3 = 108, of which some are green and other cases are non-green. Of all 108 possible cases, only 37 are green. All non-green combinations are screened out using the objective equation for the EAC system. All feasible green combinations are those cases with unavailability hours greater than zero as shown in Figure 1 (Ref. 3). Following the same process, other MSPI systems have their own optimization equations and GREEN combinations.

	TRN1A-A.X	TRN1B-B.X	DG.Ns	DG.Nl	DG.Nr	DG.Xs	DG.Xl	DG.Xr	MGN
	1.53E-09	1.53E-09	5	5	2	6.64E-07	6.53E-07	2.59E-06	3.36E
1	1095.83	1095.83	0	0	0	0.00E+00	0.00E+00	0.00E+00	3.35E
2	932.86	932.86	0	0	1	0.00E+00	0.00E+00	2.09E-06	2.85E
3	87.68	87.68	0	0	2	0.00E+00	0.00E+00	2.09E-06	2.69E
4	932.86	932.86	0	1	0	0.00E+00	1.53E-07	0.00E+00	2.85E
5	720.08	720.08	0	1	1	0.00E+00	1.53E-07	2.09E-06	2.21E
6	-125.1	-125.1	0	1	2	0.00E+00	1.53E-07	2.09E-06	-3.84E
7	720.08	720.08	0	2	0	0.00E+00	1.53E-07	0.00E+00	2.21E
8	507.3	507.3	0	2	1	0.00E+00	1.53E-07	2.09E-06	1.55E
9	-337.87	-337.87	0	2	2	0.00E+00	1.53E-07	2.09E-06	-1.04E
10	507.3	507.3	0	3	0	0.00E+00	1.53E-07	0.00E+00	1.55E
11	294.52	294.52	0	3	1	0.00E+00	1.53E-07	2.09E-06	9.04E
12	-550.65	-550.65	0	3	2	0.00E+00	1.53E-07	2.09E-06	-1.69E
13	294.52	294.52	0	4	0	0.00E+00	1.53E-07	0.00E+00	9.04E
14	81.75	81.75	0	4	1	0.00E+00	1.53E-07	2.09E-06	2.51E
15	-763.43	-763.43	0	4	2	0.00E+00	1.53E-07	2.09E-06	-2.34E
16	81.75	81.75	0	5	0	0.00E+00	1.53E-07	0.00E+00	2.51E

Fig. 1. The Screening for the Green Combinations.

Assume only one failure occurs at a time, the green combinations can be ordered according to the number of failures. The MSPI sequence and scenarios can be determined in advance as shown in Figure 2 (Ref. 3), where the link is the feasible failure path that the MSPI index remains green. Provided that the PRA model is finalized at a time freeze point and the operating data is set (critical hours, demand, and running hours), this figure shows that all the MSPI green combinations are defined and mapped in advance, and corresponding management actions are able to be planned ahead of time.

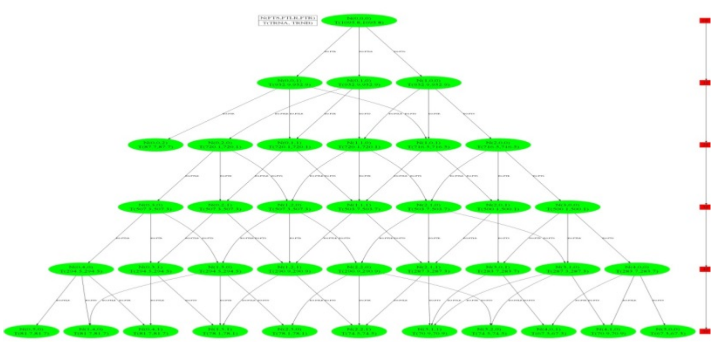

Fig. 2. Visualization of EAC Green Combinations (Maximization of Green Margin)

V. CONCLUSIONS

MSPI is a comprehensive index that reflects implicitly or explicitly the as-built, as-operated, as-maintained and as-planned Nuclear Power Plants (NPP). Overall, the MSPI index is not only able to measure how well the performance of mitigating systems are, but also it can be the index of selecting better plant designs and modifications for better safety and performance. The design or modification to gain more MSPI margin also leads to the improvement of being a safer and more robust plant.

Once the PRA and plant data are known, all green combinations can be determined for all the MSPI systems in advance. Based on the risk and MSPI insights, a plant is able to predefine strategy and make proactive decisions rather than response passively. Better MSPI management and performance means safer plant operation.

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