An Investigation of MSPI Optimization to Improve NPP Safety and Efficiency

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INTRODUCTION

Mitigating System Performance Index (MSPI) is one of the risk-informed, plant-specific performance indicators (PIs) employed by the U.S. Nuclear Regulatory Commission (NRC) for the Reactor Oversight Process (ROP). MSPI is largely used by nuclear regulators and industrial partners to monitor and assess the performance of nuclear power plant (NPP) mitigating systems. The MSPI was initially developed by the NRC's Office of Nuclear Regulatory Research (RES) to replace the previously adopted safety system unavailability (SSU) PI because the NRC and industry identified several drawbacks associated with the use of SSU PI in the ROP [1].

To improve NPP safety and cost efficiency, Tennessee Valley Authority (TVA) and the Idaho National Laboratory (INL) Enhanced Resilient Plant (ERP) project team collaborated and conducted an optimization study on MSPI using advanced artificial intelligence (AI) and machine learning (ML) techniques [2, 3]. The objectives of this study include the follows:

- develop a process to optimize MSPI with data-informed reasoning for off-normal equipment conditions,
- utilize the ranking of root causes and potential resolutions to identify the best option of economically reducing MSPI value,
- facilitate and simplify risk-informed decision-making for continuous improvement.

This process not only can be used along with existing risk-informed programs of the plant, but also can be extended to other industry or plant-specific performance indexes.

This paper provides an overview of MSPI and describes how MSPI is evaluated in the current MSPI program. Two proposed MSPI optimization approaches as well as the three major tasks for developing the MSPI optimization process are introduced. An integrated MSPI calculation tool was developed by integrating plant operating data, probability risk assessment (PRA) data, and industry baseline values to automate the MSPI calculation process and report generation.

MSPI OVERVIEW

According to Nuclear Energy Institute (NEI) report NEI 99-02 [4], "Regulatory Assessment Performance Indicator Guideline," the purpose of the MSPI is to monitor the performance of selected systems based on their ability to perform risk-significant functions. The MSPI is calculated individually for each of the mitigating systems that are chosen to be monitored in the MSPI program for pressurized water reactor (PWR) and boiling water reactor (BWR) (see Table I). In general, these mitigating systems are selected with their importance and capability in mitigating the effects of initiating events to prevent core damage (CD). In the current practice, each reactor unit has MSPIs for five safety-important systems. The MSPI is used to determine the cumulative significance of the system/component failures and unavailability over the monitoring time period.

TABLE I. Mitigating Systems for PWR and BWR.

Index[a]	PWR Systems	BWR Systems
MS06	Emergency AC (EAC) Power Systems	EAC Power Systems
MS07	High Pressure Injection (HPI) System	HPI System
MS08	Auxiliary Feed Water (AFW) System	Reactor Core Isolation Cooling (RCIC) System (or isolation condenser)
MS09	Residual Heat Removal (RHR) System	RHR System
MS10	Cooling Water Support (CWS) System[b]	CWS System[b]

[a] The index numbering does not start with 01 because the MSPIs discussed in this section are part of the NRC regulatory assessment performance indicators [3].
[b] Cooling water support system includes service water, component cooling water, or the equivalent system.

The MSPI is calculated for each monitored mitigating system and is the sum of the Unavailability Index (UAI) and the Unreliability Index (URI) due to unavailability (UA) and unreliability (UR) of the system, respectively:

$$MSPI = UAI + URI \tag{1}$$

$$UAI = CDF_P \sum_{i=1}^{n} \left(\frac{FV(UA_i)}{UA_i} (UA_{ci} - UA_{bi}) \right) \tag{2}$$

$$URI = CDF_P \sum_{j=1}^{n} \left(\left[\frac{FV(UR_j)}{UR_j} \right]_{\max} (UR_{cj} - UR_{bj}) \right) \tag{3}$$

where:

CDF_P = Plant-specific core damage frequency

FV = Fussell-Vesely importance measure of a train or component

UA_i = Plant-specific train i unavailability
UA_{ci} = Current train i unavailability
UA_{bi} = Baseline train i unavailability
UR_j = Plant-specific component j unreliability
UR_{cj} = Current component j unreliability
UR_{bj} = Baseline component j unreliability

As shown in Table II, a performance color is assigned to one MSPI result for each mitigating system according to the MSPI numerical value and the Performance Limit (PL).

TABLE II. MSPI Limits and Color Scale.

Condition	Performance Color
MSPI $\leq 10^{-6}$ and $F_a \leq F_m$	GREEN
MSPI $\leq 10^{-6}$ and $F_a > F_m$	WHITE
$10^{-6} <$ MSPI $\leq 10^{-5}$	
$10^{-5} <$ MSPI $\leq 10^{-4}$	YELLOW
MSPI $> 10^{-4}$	RED

where:
F_m = Maximum number of component failures
F_a = Actual number of component failures

MSPI OPTIMIZATION METHODS

Two types of MSPI optimization approaches are proposed (see Fig. 1). One is PI/MSPI oriented approach in which MSPI optimization process can be developed based on data, PRA model, and plant operation inputs, with the following stages:

- Data collection and characterization stage: collect the parameters of plant designs and baselines, as well as the immediate plant operation data.
- Calculation stage: develop optimization equations and enumerate all the acceptable PI cases.
- Visualization stage: present the data in graphs for decision-making.

The other one is a data-oriented approach in which the MSPI optimization process starts from a target PI and dives into the database to identify the contributing events and find the root causes from the data analysis of the numeric and text data and summarize the information for resolutions.

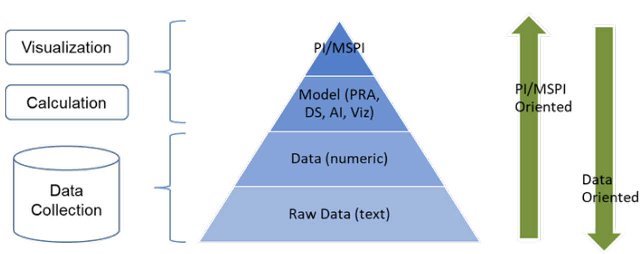

Fig. 1. MSPI optimization approaches.

The development of MSPI optimization methodology is an interdisciplinary effort. It is a fusion of technical fields of PRA modeling, data science (DS) techniques (e.g., big data, statistic and probability, data mining techniques), AI and ML techniques including natural language processing (NPL), decision trees, and visualization.

MSPI OPTIMIZATION TASKS

To reduce risk, improve reliability, and build a model for risk-informed decision-making, there are three major tasks in developing the MSPI optimization process:

1. Develop MSPI system objective functions.
2. Extend MSPI system objective functions and fuse with AI technique.
3. Develop MSPI plant objective function by aggregating system objective functions into one plant level MSPI optimization function.

Task 1 Develop MSPI system objective functions

This task will derive and implement system objective functions in the existing MSPI program. With all the information in the MSPI margin objective equation, the analyst can pre-define the maximum allowed combinations of UA time and UR failures for each system and closely monitor the low-margin MSPI systems, thus the MSPI margin and risk can be tightly controlled and keep remaining green, especially when there is less margin (e.g., no more than three UR failures).

Task 2 Extend MSPI system objective functions and fuse with AI techniques

This task planned for this step includes two subtasks. The first subtask is to develop a method to find the root cause of the risk-significant contributors to the risk importance such as initiating event frequency, equipment failure probability or rate, operator action, etc. Using the PRA software like SAPHIRE, the risk-significant contributors can immediately become available after the PRA model is quantified. However, it can be a tedious, labor-intensive, and time-consuming process to look into the root cause of the risk-significant contributors and find the related potential events in the industry operating experience (OpE) database. Such a process can be automated and empowered using AI techniques to search and group the root causes and extract supporting information such as time, correlation, frequency, and potential solutions from OpE database. Based on risk or cost significance, using AI techniques like ML and pattern recognition can help to rank the causes and corrective actions.

The other subtask is to develop a method to balance maintenance cost/frequency and reliability improvements for risk significant equipment. The goal is to reduce maintenance frequency while maintaining or improving risk metrics.

Task 3 Develop MSPI plant objective function

The above optimization/objective equations are the MSPI margin management at a system level. It can be extended to plant level by aggregating five MSPI system objective functions into one MSPI plant objective function, so the plant can focus its resource and efforts on the risk-important structures, systems, and components (based on PRA and 10 CFR 50.69 risk application) efficiently.

MSPI CALCULATION TOOL

To develop the MSPI optimization process, the calculation of MSPI is required to be performed first. Normally the MSPI calculation in the industry is performed by the INPO's Consolidated Data Entry web-based tool. However, this tool is only available to its members. Other MSPI calculation tools developed by various companies are available for purchase. In this section, an MSPI calculation tool has been developed using the Python programming language, by incorporating the plant operation data, PRA data, and industry baseline values to automate the calculation process of MSPI and generation of the report.

The MSPI calculation tool starts from raw industry data as well as plant-specific data for IEs, equipment reliability, and unavailability, etc. In addition, the system-level and plant-level PRA modeling (plant design, operation, maintenance, operator actions, etc.), PRA quantification and risk insights, PI/MSPI program (plant online time, system train unavailable time and equipment unreliability failures, engineering data, expected baselines) are taken into account.

The MSPI calculation flow chart is depicted in Fig. 2. In general, the calculation is performed in five major steps:

- Determine the MSPI system
- Identify the trains and components of the selected MSPI system
- Data collection and input file preparation: including the system information, operation and maintenance data, and PRA data
- MSPI calculation with frontstop (risk cap) and backstop (performance limit) incorporated
- Result generation

To examine the applicability and validation of the algorithm, the MSPI calculation tool was tested with the data from a collaborating NPP. The EAC system of this plant was selected. The calculated MSPI value generated by the MSPI tool for Unit 1 and Unit 2 agrees well with the one from the plant which demonstrates the feasibility of the calculation tool.

CONCLUSIONS

This paper presents an investigation of the MSPI optimization approach to improve the safety and efficiency of the NPPs. The background information on MSPI as well as how MSPI is evaluated in the current MSPI program are described. Two proposed MSPI optimization approaches as well as the three major tasks for developing the MSPI optimization process are introduced. As the first step of the integrated MSPI calculation and optimization process, an MSPI tool was developed with the incorporation of the plant operation data, plant PRA data, and industry baseline values to automate the calculation process of MSPI and the generation of MSPI report. The tool was verified with the example data sets from an NPP. The case study demonstrates the feasibility of the proposed calculation tool.

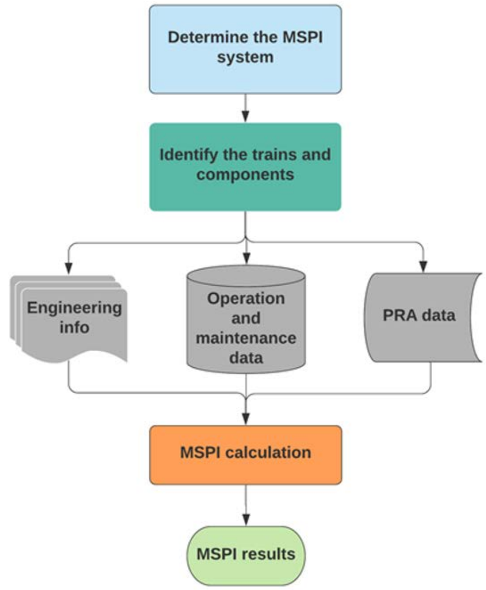

Fig. 2. MSPI calculation flowchart.

This work is only the first stage in an effort to optimize the MSPI through advanced AI and ML techniques to improve NPP safety and efficiency. Future research efforts will be dedicated to applying AI and ML techniques the development of an MSPI optimization process.

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REFERENCES

[1]. U.S. NRC, "Independent Verification of the Mitigating Systems Performance Index (MSPI) Results for the Pilot Plants," NUREG-1816 (2005).

[2]. S. ZHANG, et. al., "Risk-Informed Analysis for Enhanced Resilient Nuclear Power Plant with Initiatives including ATF, FLEX, and Advanced Battery Technology," INL/EXT-21-64546, Idaho National Laboratory (2021).

[3]. H. JIANG and Z. LI, "MSPI Driven Safer Nuclear Power Plant – Callaway Energy Center," The 2015 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2015), Sun Valley, Idaho, USA, April 26-30 (2015).

[4]. NEI, "Regulatory Assessment Performance Indicator Guideline," NEI 99-02, Rev. 7 (2013).