Energy Facility Contractors Group (EFCOG)

Safety Culture Community of Practice (CoP)

White Paper

Interpretive Guide to "Understanding the relationship between safety culture and safety performance indicators in U.S. nuclear waste cleanup operations"

Prepared by: Adrienne King Digitally signed by Adrienne King Date: 2023.11.02 07:46:31 -07'00'
Adrienne King — Date
Pacific Northwest National Laboratory
EFCOG Safety Culture CoP Member

Prepared by: DAVYDA HAMMOND (Affiliate) Digitally signed by DAVYDA HAMMOND (Affiliate) Date: 2023.11.08 09:17:58 -05'00'
Davyda Hammond — Date
Oak Ridge Associated Universities
EFCOG Safety Culture CoP Member

Approved by: CHERYL MACKENZIE (Affiliate) Digitally signed by CHERYL MACKENZIE (Affiliate) Date: 2023.11.02 10:40:06 -04'00'
Cheryl MacKenzie — Date
Sandia National Laboratories
EFCOG Safety Culture CoP Chair

Approved by: Timothy McEvoy Digitally signed by Timothy McEvoy Date: 2023.12.13 13:15:23 -05'00'
Tim McEvoy — Date
Consolidated Nuclear Security, LLC
EFCOG Integrated Safety Management System Task Working Group Chair

SUMMARY

Anecdotally, the safety culture community of practice (CoP) within both the Energy Facility Contractors Group (EFCOG) and the U.S. Department of Energy (DOE) contractor safety culture subject matter experts (SMEs) have a widely varied background. This may include extensive social science and research experience, backgrounds in industrial safety or hygiene, human resources, etc. This white paper (WP) is specifically intended for those without a research background, to provide an overview of the structure and contents of the peer-reviewed article '*Understanding the relationship between safety culture and safety performance indicators in U.S. nuclear waste cleanup operations*' (referred to hereafter as 'the article'). Additionally, this WP provides a cost-benefit analysis of replicating the effort described in the article, and associated precautions and limitations.

Contributors:

Davyda Hammond, Oak Ridge Associated Universities
Adrienne King, Pacific Northwest National Laboratory, Lead

We also want to thank the many individuals who provided their general feedback and suggestions.

DEDICATION

This document is dedicated in memory of Dr. Cindy Caldwell, past EFCOG Safety Culture Task Team chair, mentor, and social scientist.

OVERVIEW

At the most basic, a peer-reviewed article is a document that has undergone independent review by three or more impartial, expert reviewers who evaluate the quality of the paper and the research it describes. This includes the research methods and results, which should be logical in process and detailed enough to allow another party to replicate the research with a different data set. Publishing research as a peer-reviewed article is a way to both ensure an appropriate standard of quality and to introduce new research to interested audiences.

In the case of '*Understanding the relationship between safety culture and safety performance indicators in U.S. nuclear waste cleanup operations*' (Hammond, King, Joe, Miller, 2023), the benefit to performing the research and publishing the results as a peer-reviewed article was to validate an accepted belief in the safety domain using a scientifically credible approach. This article seeks to establish, to an academic standard, the validity of the Oak Ridge Associated Universities (ORAU) survey instrument and to document the effort and results with analysis for the Tank Operations Contract (TOC) prime contractor, Washington River Protection Solutions (WRPS) (referred to hereafter as the TOC).

INTRODUCTION

The Introduction provides background on safety culture within the U.S Department of Energy (DOE) complex, the involved organizations (ORAU and the TOC) and their motivations for the specific statistical analysis described in the article, and a brief overview of different types of safety culture models for performance monitoring. Important take-aways from this section include:

- The hypothesis of the paper was that there would be a correlation between changes to TOC's internally-collected performance data and statistically significant changes in safety culture data collected by ORAU's safety culture evaluations.
- The TOC has had significant run-time to collect internal performance metrics, over a decade at the time of initiation of the analysis described in this paper. There were also external, independent data sources provided by ORAU for comparison of internal metrics. Both data sources were necessary to perform the analysis.
- An event had occurred at the TOC, which drove the business decision to hire an external independent evaluator of safety culture, in this case ORAU. Not all DOE contractors will have either the interest in, or need to, hire an external party to evaluate safety culture, meaning only a small portion of the DOE contractor community will have this type of data available for comparison.

MATERIAL AND METHODS

The Material and Methods section describes the structure of the ORAU survey used at the TOC, primarily comprised of 39 "safety culture statements" and a 1-5 Likert scale by which respondents indicated their agreement. The questions were aligned with the Institute of Nuclear Power (INPO) 10 Traits of a Healthy Nuclear Safety Culture. (**Note:** the INPO traits have been cross-walked to the DOE Safety Culture Focus Areas and Attributes (DOE G 450.4-1c Attachment 10) and the crosswalk is available on the EFCOG Safety Culture CoP website).

The survey was deployed at the TOC in 2017 and again in 2020; results indicated statistically significant improvement in several of the question categories. The survey results were then compared with a suite of TOC performance indicators to see whether the changes to the data over a period of time correlated with the survey results.

RESULTS

The results section provides a description of the statistically significant correlations found between the survey and performance data at the TOC, information on the correlations between safety culture traits and the TOC's internal measures of performance, where correlations were found, and how they were calculated. Additionally, speculation is provided as potential explanations for the correlations that are found, though identifying the source(s) of those correlations was outside of the scope of this article.

Note: identifying a correlation between the performance of two data streams does not mean that the measured variables impact or interact with each other (i.e., "correlation does not imply causation"). Correlation implies an underlying condition impacting both measured variables; an example might be "sunscreen use" and "ice cream sales" which may be correlated, but which are both directly impacted by sunny, hot weather. However, it is also possible that correlations may be entirely incidental, which is why robust initial analysis and ongoing monitoring are required. The bar for determining causation in scientific experimentation is much higher and is difficult in the context of social science and organizational culture due to the number of variables that make control nearly impossible.

DISCUSSION

The Discussion section of the article provides context from other publications, describes limitations to the research described in the article, and draws conclusions. The evaluation of implications from other published peer-reviewed articles offers some examples of data interpretation. The limitations delineate the challenges associated with analysis of proprietary performance data. The conclusions confirm that statistically significant correlations were found between the survey and performance data at the TOC.

REPLICATION

While all DOE prime contractors have performance indicators (PIs) or metrics (those that are required and standardized (e.g., injury data, or occurrence reporting) or those associated with the Contractor Assurance System (CAS)), most contractors have different specific missions, success criteria, and PIs meaningful to safety or organizational culture. Additionally, injury and occurrence reporting tend to be lagging indicators. A benefit of identifying contractor PIs that are correlated with culture is that it provides measures to monitor performance between largescale culture evaluation efforts (which are usually performed on an 18-36 month cycle). The PIs can be potentially monitored as an early indicator of efficacy of culture improvement efforts or to identify conditions or performance associated with adverse culture impacts.

However, there are specific resources necessary to replicate the statistical analysis performed in the article, as well as considerations for when undertaking the effort is of value to an organization. Two important general considerations for an organization curious about whether to replicate this effort are offered:

1. **Is there a business need to identify metrics correlated to safety culture performance?**

   These could include contract direction (either within the prime contract or via a letter of direction) or as part of corrective actions for an event. This could also include interest by senior management or corporate oversight. As a baseline, safety culture metrics are often a subset of performance indicators derived from CAS performance indicators.

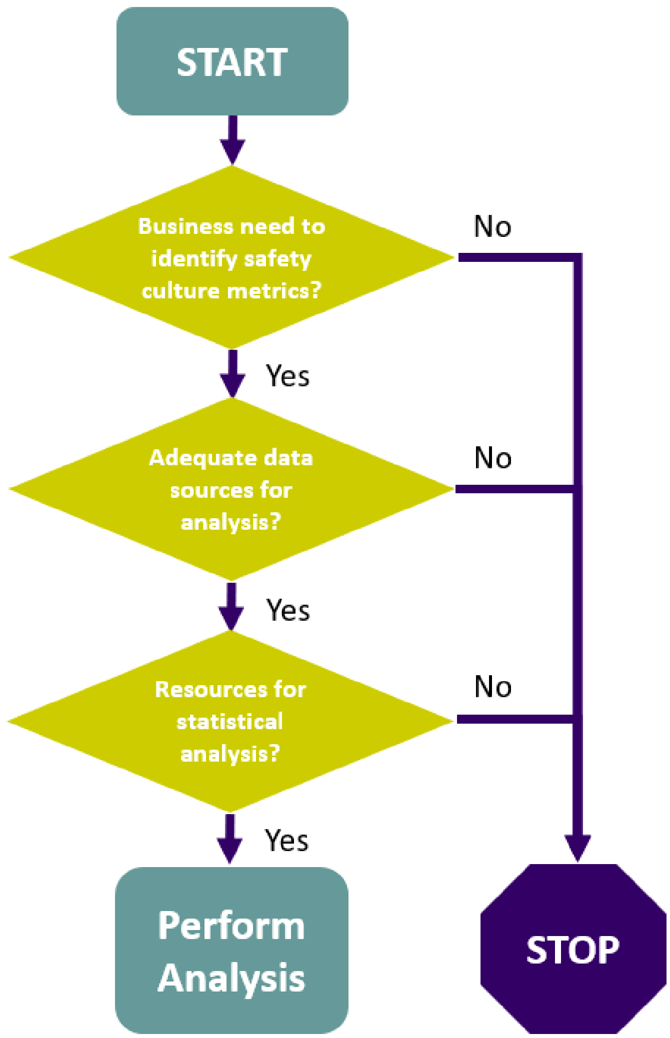
   For a correlation and/or regressive analysis, are there at least two types of data sources, gathered over three or more years, with statically significant changes in performance? Ideally one source would be independently gathered. The relevant data should be gathered and evaluated for data integrity and continuity before starting analysis. The more data available, over a longer period of time, the better, though it is important to verify whether collection methods and data type have stayed the same for the duration.

2. **Is access to the appropriate resources for statistical analysis available?**

   This includes trained statisticians or data scientists and appropriate software (e.g., R Studio). While R Studio is free, cybersecurity and information technology should be consulted before installing on machines owned by the DOE.

If the answer to any of these questions is "no," then the organization is missing the necessary components to replicate the analysis performed in the article. Newer contracts (only a few years old) will not have the 'run-time' necessary for performance indicators, and data from survey instruments (internal or external), also need the opportunity for multiple deployments. The reference section of this document has information on EFCOG and DOE Safety Culture Improvement Panel (SCIP) Monitoring Means and Methods Working Group (MMMWG) guidance as of the date of publication of this white paper. Additional information and considerations are provided in the next section.

Note: while neither this white paper nor the article is intended to promote the ORAU survey instrument, the ORAU survey instrument serves as an excellent model for the level of validation and independence ideal for data collection for comparison to performance metrics. Other types of survey instruments (internal or external) can be used as well but will ideally be scientifically validated and similarly administered with the exact same questions over a multi-year period.



ALTERNATIVES

As mentioned previously, organizations may not have existed long enough or have consistently collected the same PIs for long enough duration to have data continuity for internal metrics. For newer organizations intending to position themselves to replicate this research must first:

- Establish internal, validated survey instruments for comparison to internal metrics, and/or consider hiring a third party to provide periodic evaluations.

- Implement or continue with current DOE norms/best practices in establishing safety culture metrics (see SCIP MMMWG and EFCOG documents).
- Establish predictive measures or another type of organizational culture performance indicator framework.
- At the time of this document (FY24), efforts were underway by the EFCOG Safety Culture CoP to develop a comprehensive guide on survey instruments, including a validation effort. The product of these efforts will be of use to organizations seeking to establish or validate their own survey instrument as a data stream for analysis against performance metrics. Additionally, there are existing documents from the SCIP MMMWG and EFCOG that provide examples of "what good looks like," which are captured in the references listed below. Other models outside of the DOE complex can also be considered. For example, "Safety Culture and Hight-Risk Environments" by Dr. Cindy Caldwell outlines a model and provides examples within its Introduction section in the peer-reviewed paper.

As a final precaution, data integrity is key; changing the type of data collected or the way that it is counted in internal performance measures and metrics resets the run-time of the metrics. Additionally, changes to internal or external survey questions or entire surveys creates data continuity challenges.

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APPENDIX A: Understanding the relationship between safety culture and safety performance indicators in U.S. nuclear waste cleanup operations'

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Understanding the relationship between safety culture and safety performance indicators in U.S. nuclear waste cleanup operations

Davyda M. Hammond [a,*], Adrienne L. King [b], Margaux Joe [c], Jeffrey R. Miller [d]

[a] Oak Ridge Associated Universities, P.O. Box 117 MS-45, Oak Ridge, TN 37831-0117, USA
[b] Pacific Northwest National Laboratory, 902 Battelle Blvd, Richland, WA 99354, USA
[c] Ohio State University, College of Public Health, 174 West 18th, Columbus, OH 43210, USA
[d] Oak Ridge Associated Universities, P.O. Box 117 MS-33, Oak Ridge, TN 37831-0117, USA

A R T I C L E I N F O

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A B S T R A C T

The relationship between nuclear safety culture and safety performance remains uncertain due to the limited research directly comparing these two variables. This study aimed to help address that gap in knowledge by evaluating the relationships between safety culture traits and two types of performance measures – personal safety and operations indicators – for a U.S. nuclear waste cleanup contractor.

Data for 29 performance indicators were correlated with data measuring workforce perceptions on safety culture traits defined by the Institute of Nuclear Power Operations (INPO). Correlation and regression analyses indicated statistically significant relationships between safety culture traits and multiple organizational key performance indicators related to safety, quality and cost savings. Higher scores on safety culture traits were more closely associated with key performance indicators related to the evaluation and resolution of safety concerns, the recognition and accurate categorization of self-revealing and self-identified issues, and emergency response actions. The results suggest that while management strategies to improve safety culture may be linked to key performance indicators that strengthen overall organizational performance, these same strategies may also indirectly degrade the work environment in other areas. These research findings can help managers and safety professionals establish key performance indicators and safety culture metrics that are meaningful indicators of safety performance and inform action plans that improve productivity, enhance workplace safety, and avoid unintended consequences.

1. Introduction

Safety culture has become a construct of great interest within the U. S. Department of Energy (DOE) since its importance was highlighted in recommendation 2011-1 (DNFSB, 2011) from the Defense Nuclear Facility Safety Board (DNFSB). The subsequently issued DOE Implementation Plan (U.S. DOE, 2011b) required assessment, monitoring, and sustainment of a healthy safety culture for energy facilities contractors. Many different tools exist for indirect measurement of the construct of safety culture (Guldenmund, 2007). While guidance documents prepared by subject-matter experts help inform safety culture activities (Energy Facilities Contractor Group, 2015), the criterion-related validity of safety culture survey assessments, such as those recommended and deployed by DOE, requires further research. The goal of this research is to address this concern by assessing the relationship between safety culture and relevant organizational safety culture outcomes within an energy facility contractor, Washington River Protections Solutions (WRPS). Our hypothesis is that there will be a positive relationship between safety culture survey and organizational performance data, indicating that a more positive perception of safety culture by the workforce translates into a higher level of safety performance.

There are myriad existing safety culture models by which an organization can define and monitoring performance of the safety or organizational culture (Cooper, 2000). For the purposes of DOE prime contractors, the relevant definition of safety culture is as follows: Safety culture is an organization's values and behaviors modeled by its leaders and internalized by its members, which serve to make safe performance of work the overriding priority to protect the workers, public, and the

* Corresponding author at: Safety Culture Program Manager, Health Sciences Division, Oak Ridge Associated Universities (ORAU).
E-mail addresses: Davyda.Hammond@orau.org (D.M. Hammond), adrienne.king@pnnl.gov (A.L. King), joe.26@osu.edu (M. Joe), jeff.miller@orau.org (J.R. Miller).

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environment (DOE, 2011a). However, DOE prime contractors looking to establish their own safety culture monitoring methods may wish to refer not just to the DOE strategy or related literature reviews (Cole et al., 2013; Guldenmund, 2000), but to other models based on empirical data collection which can be applied to the DOE definition of culture. Reniers (2010) presents an integrative model – the P2T model - to simultaneously study safety and security culture and climate with a focus on people, procedures, and technology. Caldwell (2017) provides a model for identifying high risk performance areas within an organization based on triangulation of risk and engagement data. The TEAM (The Egg Aggregated Model) model provides an overview of how safety culture concepts are cyclical in nature and can be integrated to enhance organizational culture (Vierendeels et al., 2018). Stemn et al. (2019) presents a framework for linking safety culture maturity with safety performance metrics within the mining industry. The Integrated Safety Culture Assessment (ISCA) (van Nunen et al., 2022) provides an empirical, safety science-based construct for safety culture. Furthermore, Many safety culture frameworks include the noted organizational culture model developed by Edgar Schein (Schein and Schein, 2017) as a part of their construct.

This paper serves as an example of using existing data to identify potentially meaningful data for safety culture monitoring within an organization. DOE prime contractors have certain standards by which performance data is collected and monitored in accordance with the prime contract, but the "how" of data collection, including performance thresholds, data continuity, etc. is variable.

The first and most obvious organizational safety outcome of interest is the number of safety incidents (e.g., occupational injuries and illnesses) recorded over the relevant time frame of safety culture survey assessment, followed closely by near misses. However, a fundamental issue with criterion-related validation of safety culture surveys in the DOE enterprise is safety incidents and even near misses at DOE energy facilities are so rare that they serve as poor outcome variables. Without substantial variance between energy facilities or within an individual energy facility at different time points, there simply is nothing to predict, and a criterion-related validity coefficient would be misleadingly small. Furthermore, not all variations in safety performance are attributable to an organization's safety culture – natural disasters, human error, preventative maintenance, and even properly functioning safety systems can also adversely affect performance metrics (Morrow, 2012).

The DOE Office of River Protection (ORP) was established in 1998 to manage the 56 million gallons of liquid and semi-solid radioactive and chemical waste stored in 177 underground tanks at the Hanford Site Tank Farms. ORP serves as DOE line management for the Tank Farms. The Tank Farms are managed and operated by WRPS under contract to ORP. The ORP Office of the Assistant Manager for Tank Operations provides Tank Farm oversight. WRPS was owned by AECOM and Atkins with AREVA as its primary subcontractor (2007 to 2020), and is currently owned by Amentum and Atkins, with Orano as its primary subcontractor (2020 to 2023). WRPS was first awarded the Tank Operations Contract in 2007, the scope of which includes operations and construction activities necessary to store, retrieve and treat Hanford tank waste, store and dispose of treated waste, and begin to close the Tank Farm waste management areas to protect the Columbia River (Gephart, 2010).

Tank Farm waste generates chemical vapors, which collect in the headspace of the tank. These chemical vapors are vented by means of active and passive ventilation systems to prevent over pressurization of the structure and to remove flammable gases (i.e., hydrogen). Chemical vapors may also be released from the tanks due to changes in weather, maintenance activities, and/or operational activities that involve disturbing the tank waste, such as retrievals and tank-to-tank transfers. Since 1987, workers have reported exposures to vapors, with occupational disease due to overexposure documented among Hanford workers (Cherry et al., 2021). Initiatives implemented by WRPS to address the chemical vapor concerns and other safety issues include, but are not limited to:

- Annual Safety Culture Sustainment and Improvement actions (2015 to current);
- Establishing a Safety Culture Improvement Team (SCIT), composed of field workers and line managers, to identify and implement improvement initiatives (2015 to current);
- A Chemical Vapors Solutions Team (CVST), which implemented a monthly forum to communicate information on vapors to workers (2017 to current);
- A Chemical Protection Program Office (CPPO), which transitioned to a permanent worker engagement department. Efforts included a CPPO Notebook, distributed on a weekly basis to provide managers vapor-related information with which to engage their staff (2017–2019); and
- A Vapor Management Expert Panel (VMEP) to help provide independent assurance to DOE ORP, WRPS, and stakeholders that actions committed to following the Tank Vapor Assessment Team's (TVAT) report and actions resulting from any new, emergent issues are being carried out and are effective in protecting workers from potential vapor exposures.

WRPS conducted a cause analysis starting in 2014, which resulted in a need to improve oversight and extensive, multi-year corrective actions, some of which took the form of monitoring, controls, sampling, etc., while others dealt with organizational culture, including communications and safety culture. The latter included conducting an independent evaluation of the safety culture concurrent to other communications and worker engagement initiatives. To meet this objective, WRPS contracted Oak Ridge Associated Universities (ORAU) to perform an initial safety culture evaluation, including an all-employee voluntary survey, focus groups and interviews in 2017, which was repeated in 2020. The results of the 2020 Safety Culture evaluation showed statistically significant improvement in several areas compared to those of the 2017 evaluation. Analysis of the 2017 and 2020 survey data resulted in statistically significant increases in the areas of organizational learning, decision making, the identification and resolution of safety concerns, and work processes. This article represents an analysis performed by ORAU and WRPS to correlate organizational performance and safety culture.

2. Material and methods

2.1. Survey development

The survey consisted of 63 items: 39 standard safety culture statements, 13 supplemental safety culture statements, one quality check statement, eight demographic questions and two open-ended questions. The standard safety culture statements were drafted from multiple sources, including the INPO's *Traits of a Healthy Nuclear Safety Culture* (INPO, 2012), International Atomic Energy Agency's safety culture characteristics and attributes (IAEA, 2006) and DOE's Integrated Safety Management System (ISMS) attributes (DOE, 2011a). Survey participants were asked to rate their degree of agreement with each statement using a five-point Likert scale ranging from strongly agree to strongly disagree. All statements were worded so that respondents' agreement with each statement was desirable and suggestive of a healthier safety culture. Each item also included a "I prefer not to answer'' response option.

The supplemental safety culture items were drafted by subject matter experts and addressed specific aspects of interest to WRPS management, including communication and civility. The survey asked participants to respond to two open-ended questions, "Do you have any other comments about the safety culture?" and "What improvements could be made to help you feel safer while at work?" The survey also included demographic questions asking respondents to indicate their employer (permanent or contractor), department (e.g., operations, maintenance, engineering), payroll status (e.g., exempt, nonexempt, bargaining unit), job category, age, gender, and managerial status (manager or non-manager).

Traits of a Healthy Safety Culture

1. **Leadership Safety Values and Actions**: Leaders demonstrate a commitment to safety in their decisions and behaviors.
2. **Problem Identification and Resolution**: Issues potentially impacting safety are promptly identified, fully evaluated, and promptly addressed and corrected commensurate with their significance.
3. **Personal Accountability**: All individuals take personal responsibility for safety.
4. **Work Processes**: The process of planning and controlling work activities is implemented so that safety is maintained.
5. **Continuous Learning**: Opportunities to learn about ways to ensure safety are sought out and implemented.
6. **Environment for Raising Concerns**: A safety conscious work environment is maintained where personnel feel free to raise safety concerns without fear of retaliation, intimidation, harassment, or discrimination.
7. **Effective Safety Communication**: Communications maintain a focus on safety.
8. **Respectful Work Environment**: Trust and respect permeate the organization.
9. **Questioning Attitude**: Individuals avoid complacency and continuously challenge existing conditions and activities in order to identify discrepancies that might result in error or inappropriate action.
10. **Decision Making** : Decisions that support or affect nuclear safety are systematic, rigorous, and thorough.

Fig. 1. Traits of a healthy safety culture.

Table 1
Cross Reference of the INPO Traits for a Healthy Nuclear Safety Culture to the DOE ISMS Safety Culture Attributes.

INPO Category	INPO Trait	DOE Safety Culture Focus Area	DOE Associated Attribute
Individual Commitment to Safety	Personal accountability	Employee/Worker Engagement	Personal commitment to everyone’s safety
	Questioning attitude	Organizational Learning	Questioning attitude
	Effective safety communication	Leadership	Open communication and fostering an environment free from retribution
Management Commitment to Safety	Leadership safety values and actions	Leadership	Demonstrated safety leadership
			Management engagement and time in field
			Staff recruitment, selection, retention, and development
			Clear expectations and accountability
		Organizational Learning	Credibility, trust and reporting errors and problems
	Decision-making	Leadership	Risk-informed, conservative decision making
	Respectful work environment	Employee/Worker Engagement	Teamwork and mutual respect
Management Systems	Continuous learning	Organizational Learning	Performance monitoring through multiple means
			Use of operational experience
	Problem identification and resolution	Leadership	Open communication and fostering an environment free from retribution
		Employee/Worker Engagement	Mindful of hazards and controls
			Participation in work planning and improvement
		Organizational Learning	Effective resolution of reported problems
	Environment for raising concerns	Leadership	Open communication and fostering an environment free from retribution
	Work processes	Employee/Worker Engagement	Participation in work planning and improvement

2.2. Survey administration and participation

Lists of personnel, including long-term contractors, were obtained from the facility, and all personnel were invited to participate in the survey. The survey was administered in paper and electronic format. A paper survey was distributed to workers who did not have access to a computer. The paper surveys were printed and placed in pre-labeled return envelopes. The paper surveys were distributed by the research team during planned workday sessions. The electronic surveys were collected using Novi Survey®, a web-based application, and e-mail invitations with a link to the survey were sent to all facility personnel.

No personal identifying information was collected during survey administration (i.e., no names, user identification, employee identification number). Participation was voluntary and results were confidential. Only ORAU personnel had access to the completed surveys/raw data. Senior management announced the survey, sent out reminders,

Table 2
Intraclass correlations for the 10-factor model.

	ICC	F	p-value	Lower 95%	Upper 95%
2017	0.38	31.8	0	0.351	0.409
2020	0.386	32.5	0	0.357	0.414
All	0.383	32.2	0	0.358	0.409

Note: ***p-value = 0 conveys that the p-values are less than the smallest representable positive double-precision floating point value.

Table 3
Intraclass correlations for the 4-factor model.

	ICC	F	p-value	Lower 95%	Upper 95%
2017	0.587	9.72	8.70E-11	0.421	0.699
2020	0.571	8.71	1.13E-12	0.425	0.675
All	0.579	9.18	8.03E-12	0.425	0.686

Table 4
Information on organizational performance measures.

KPI Name	Timeframe[1] (Letter Code)	Authority
Days Away, Restricted, Transferred Case Rate - Number of DART Cases	Q (A), M (B)	Internal
Total Recordable Case Rate - Number of Recordable Cases	Q (B), M (C)	Internal
First Aid Case Rate - First Aid Cases	Q (C), M (D)	Internal
Stop Works Issued - # of Stop Works Issued	Q (D), M (E)	Internal
Medical Appointment No-Shows - Total No-Shows	Q (E), M (F)	Internal
Regulatory Notices of Correction / Violation - Number of Inspections	Q (F), M (G)	Internal
Environmental Notifications - Planned Outages & Other Notifications	Q (G), M (H)	External
Radiological Contamination Events - Potentially Contaminated Liquid Contact	Q (H)	Internal
Radiological Contamination Events - RadCon Adherence Deficiencies	Q (I)	Internal
Radiological Contamination Events - Contamination Discovery Events	Q (J)	Internal
Radiological Contamination Events - Rad Containment Deficiencies	Q (K)	Internal
Radiological Contamination Events - Total Contamination Events	Q (L)	Internal
Self-Identified Issues - Self-Revealing	Q (M), M (I)	Internal
Self-Identified Issues - Externally-Identified	Q (N), M (J)	External
Self-Identified Issues - Self-Identified	Q (O), M (K)	Internal
Emergency Preparedness Evaluated Drill Performance – Average Drill Score	Q (P), M (L)	Internal
Operations Drill Activity	Q (Q), M (M)	Internal
Issue Evaluation Timeliness – Evaluations Completed	Q (R), M (N)	Internal
Issue Evaluation Timeliness – Pending Evaluations	Q (S), M (O)	Internal
Issue Evaluation Timeliness – Avg. Age of Pending Evaluations	Q (T), M (P)	Internal
Issue Evaluation Timeliness – Percentage 45-days Old	Q (U), M (Q)	Internal
Issue Resolution Timeliness – Action Requests Initiated	Q (V), M (R)	Internal
Issue Resolution Timeliness – Condition Report (CR) Corrective Action Extensions	Q (W), M (S)	Internal
Issue Resolution Timeliness – Open CRs (Backlog)	Q (X), M (T)	Internal
Issue Resolution Timeliness – Average Age of Open CRs	Q (Y), M (U)	Internal
Issue Resolution Timeliness – Issue Resolution Timeliness Index	Q (Z), M (V)	Internal
Management Observation Program (MOP) Worksite Visit (WSV)Participation – Senior Management WSV or MOP Participation	Q (AA), M (W)	Internal
MOP WSV Participation – Level 2&3 Management MOP Participation	Q (BB), M (X)	Internal
MOP WSV Participation – Overall Participation	Q (CC), M (Y)	Internal

Note: Data Range 1 includes available data prior to and through the completion of the 2017 Safety Culture Evaluation, while Data Range 2 includes data from after the 2017 Safety Culture Evaluation through the completion of the 2020 Safety Culture Evaluation.

and encouraged participation. ORAU sent up to two reminder e-mails to people who did not respond to the first invitation, until a 50% minimum response rate was obtained.

The 2017 safety culture survey was conducted from May 31, 2017 through August 4, 2017. The population of the WRPS workforce at the time of the survey was estimated at 2,696. A total of 1,529 surveys were received, 969 electronic and 560 hard copy. The final response rate was 57% (1529/2696). The survey participants were considered representative of the WRPS workforce (Baruch and Holtom, 2008). The majority of survey participants (74.5%) worked for WRPS. The remaining participants identified themselves as subcontractors (13%) or chose to not answer this survey item (12%). Approximately one-third (33%) of the participants indicated their job category as professional level. Professional employees are non-supervisory personnel who perform specialized work (e.g., engineering, financial, technical). Participants indicating they were working level employees accounted for slightly less of the responses (26.8%). Working level employees are non-supervisory personnel who perform common trade work (e.g., construction, operating, maintenance). Just over ten percent indicated they were management (12.7%), who oversee senior supervisory personnel (i.e., middle managers and higher-level managers), and 7% reported being a supervisor, who oversee working level personnel (i.e., foremen, group leaders, superintendent). A total of about one-fifth (19.7%) of the survey respondents identified as holding some supervisory or managerial role. Approximately one-fifth (20.5%) of survey respondents chose not to disclose their job category/supervisory or managerial status. Approximately one half (48.2%) of participants indicated that they had exempt status and were paid by salary. The rest were either part of the bargaining unit (20.7%) or indicated that they were non-exempt and paid hourly (12%). About 19% of participants chose not to answer this item.

The 2020 safety culture survey was conducted from January 20, 2020 through February 14, 2020. The population of the WRPS workforce was estimated to be 2,620 at the time of the survey. A total of 1,415 online surveys and 307 hard-copy surveys were received; therefore,

Table 5
Descriptive statistics for the quarterly organizational performance measures.

	Q1			Q2		
	Std. Dev.	Avg.	Mean	Std. Dev.	Avg.	Mean
A	0.49	0.29	0.00	0.44	0.22	0.00
B	0.90	0.86	0.00	1.09	0.78	0.00
C	5.65	23.39	N/A	3.30	17.11	20.00
D	3.36	5.57	5.00	3.40	5.56	5.00
E	58.68	167.57	N/A	29.01	103.56	98.00
F	3.00	7.00	7.00	1.51	6.44	8.00
G	7.48	9.00	0.00	1.13	2.56	3.00
H	0.90	0.86	0.00	1.13	2.56	3.00
I	1.15	2.00	1.00	2.00	1.33	0.00
J	1.27	4.43	6.00	1.41	3.67	3.00
K	1.46	1.14	0.00	0.44	0.22	0.00
L	2.37	8.43	10.00	2.55	5.56	4.00
M	6.78	17.71	N/A	7.01	21.78	19.00
N	31.33	73.57	N/A	24.08	47.22	N/A
O	75.50	573.00	N/A	105.34	601.00	574.00
P	0.08	1.94	1.90	0.25	2.50	2.50
Q	8.84	88.14	86.00	5.41	90.00	84.00
R	52.38	462.29	N/A	91.96	457.56	N/A
S	61.86	574.29	N/A	130.04	518.22	N/A
T	26.29	111.71	N/A	8.34	67.89	N/A
U	0.04	0.80	N/A	0.02	0.86	N/A
V	78.18	446.86	N/A	113.44	469.22	N/A
W	95.82	376.14	388.00	66.75	360.22	414.00
X	126.09	1917.00	N/A	336.39	1895.67	N/A
Y	6.02	127.43	N/A	7.14	116.00	123.00
Z	5.54	130.00	N/A	7.07	120.67	126.00
AA	0.03	0.87	N/A	0.09	0.75	N/A
BB	0.03	0.87	N/A	0.02	0.91	0.92
CC	0.03	0.87	N/A	0.03	0.89	0.85

Table 6
Descriptive statistics for the monthly organizational performance measures.

—	M1			M2		
	Std. Dev.	Avg.	Mean	Std. Dev.	Avg.	Mean
B	0.36	0.14	0.00	0.26	0.07	0.00
C	0.58	0.33	0.00	0.59	0.28	0.00
D	2.94	7.86	5.00	2.51	5.73	6.00
E	1.63	2.05	2.00	1.56	1.72	0.00
F	21.91	59.95	59.00	11.25	34.69	35.00
G	1.91	2.52	3.00	1.54	2.17	1.00
H	4.50	3.76	3.00	1.03	0.93	0.00
I	3.75	6.52	11.00	3.24	7.07	5.00
J	13.96	24.43	18.00	10.22	16.03	10.00
K	41.96	187.86	N/A	40.21	198.24	181.00
L	0.22	1.94	1.90	0.28	2.46	2.60
M	4.90	30.00	29.00	2.63	30.00	32.00
N	26.95	153.38	136.00	37.79	152.21	152.00
O	26.69	190.24	206.00	45.31	173.17	176.00
P	8.22	38.33	37.00	3.50	22.97	24.00
Q	0.05	0.80	0.83	0.03	0.85	0.85
R	31.63	148.52	101.00	43.34	155.31	135.00
S	38.17	124.90	119.00	27.29	120.41	125.00
T	45.27	631.38	N/A	106.11	634.21	796.00
U	9.98	130.00	124.00	8.55	116.21	111.00
V	8.00	131.43	135.00	7.50	121.17	119.00
W	0.08	0.88	0.80	0.16	0.76	0.75
X	0.05	0.87	0.83	0.05	0.91	0.95
Y	0.05	0.87	0.87	0.06	0.89	0.89

1,722 surveys were included in the analysis for a response rate of 66% (1,722/2,620). The majority of participants were employed by WRPS (74.6%). Approximately 14.0% of survey participants were subcontractors, and the remaining 11.4% chose not to disclose their employer. The majority of participants were professional level (35.3%) or working level employees (27.4%). Management accounted for 11.4% of participants, and supervisors accounted for 7.5%. The remaining 18.5% of participants chose not to disclose this information. Approximately 20% of participants indicated that they managed or supervised workers. Salary-exempt workers were most common at 49.8%, and bargaining unit employees accounted for 17.6%. Of the remaining participants, 13.6% were hourly-nonexempt workers, and 19.0% preferred not to disclose their payroll status. The methods were identical for the 2017 and 2020 surveys, and the sample populations were similar.

2.3. Safety culture measures

A survey was designed by Oak Ridge Associated Universities (ORAU) to measure organizational safety culture. The survey was developed to be consistent with DOE ISMS guidance, as well as to align with the organizational Traits of a Healthy Safety Culture as defined by INPO and the U.S. Nuclear Regulatory Commission (NRC) (Nuclear Regulatory Commission, 2011). The 10 Traits of a Healthy Safety Culture are presented in Fig. 1. DOE ISMS safety culture attributes are directly comparable to the NRC and INPO safety culture traits. A large body of previous work done at dozens of DOE sites and organizations across the U.S. focused on the ISMS safety culture attributes. Table 1 provides a cross-reference between the ISMS attributes and INPO traits.

Several measures were taken to establish the validity of the survey instrument. First, a construct validity table was prepared mapping the topic, domain, and constructs for each statement. Second, a panel of subject matter experts reviewed the statements, instrument structure, and construct validity table to determine if the instrument adequately measured the concept of safety culture. The panel of subject matter experts included representatives from Hanford Atomic Metal Trades Council (HAMTC) along with members of the SCIT, CVST, and the WRPS Employee Accident Prevention Council (EAPC). Statements were modified based on their feedback. Finally, the instrument was field tested with over 60 nuclear workers to determine if the statements had content validity and if the structure of the instrument was appropriate. Statement structure and wording were modified based on their feedback. With a Cronbach's alpha of 0.97, the survey demonstrated internal consistency.

2.4. Factor analysis

Preliminary analyses of safety culture data collected at WRPS in 2017 and 2020 indicated there was collinearity among the safety culture traits. Based on these results, a 10-factor exploratory factor analysis was performed to investigate if and which of the 10 safety culture traits were highly correlated. Intraclass correlations (ICC) were used to determine the within-group reliability of the WRPS survey data. ICC estimates and 95% confident intervals were calculated using RStudio version 3.6.1 based on a two-way random-effects model with a mean-rating ($k = 4$) and absolute-agreement.

Based on the 95% confident interval of the ICC estimate, values <0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li, 2016). The ICC values (<0.39) for the 2017/2020 10-factor model showed poor absolute agreement (Table 2). The 2017/2020 4-factor data showed moderate absolute agreement (ICC < 0.59) and are shown in Table 3. All values for the 10-factor and 4-factor model are statistically significant ($p < 0.001$). These results show poor to moderate collinearity among the factors within the 10-factor and 4-factor models indicating that the factors are unique and independent of each other.

2.5. Performance measures

WRPS identified 29 organizational performance measures, or key performance indicators (KPIs), for inclusion in the analysis, which included a variety of personal safety and operational indicators. The WRPS Contract Award Fee metric was not included in the analysis since it did not meet the temporal data criterion (e.g., quarterly or monthly data capture); however, the WRPS Contract Award Fee increased (i.e., improved) during the study timeframe.

Table 7
Descriptions of the safety culture factors.

Factor	Original INPO/NRC Trait Names	Factor Definition
Factor 1 (F1)	Decision Making; Work Processes	The process of planning and controlling work activities is implemented so that safety is maintained through decisions made to systematically, rigorously, and thoroughly support nuclear safety, as well as through opportunities to learn about ways to ensure safety are sought out and implemented. This process includes the prompt identification, full evaluation, and prompt addressing and correcting of issues potentially impacting safety, commensurate with their significance.
Factor 2 (F2)	Personal Accountability; Questioning Attitude	All individuals take personal responsibility for safety, avoid complacency, and continuously challenge existing conditions and activities in order to identify discrepancies that might result in error or inappropriate action.
Factor 3 (F3)	Respectful Work Environment; Environment for Raising Concerns	A safety conscious work environment is maintained where trust and respect permeate the organization, and personnel feel free to raise safety concerns without fear of retaliation, intimidation, harassment, or discrimination.
Factor 4 (F4)	Leadership Safety Values and Actions; Effective Safety Communication	Leaders demonstrate a commitment to safety in their decisions and behaviors, as well as provide clear communications that maintain a focus on safety.

Quarterly estimates were available for all 29 measures and monthly estimates were available for 24 of the measures. The five measures in which monthly estimates were not available were connected to radiological contamination events. The date ranges used for the organizational performance measures (shown in Table 4), hereafter referred to as Quarterly (Q)/Monthly (M) Data Range 1/2, are as follows:

- Quarterly Data Range 1 (Q1): 3QFY16 through 1QFY18;
- Monthly Data Range 1 (M1): February 2016 through October 2017;
- Quarterly Data Range 2 (Q2): 2QFY18 through 2QFY20; and,
- Monthly Data Range 2 (M2): November 2017 through March 2020.

Organizational performance data were collected to correlate performance with the safety culture survey periods. As such, the analysis compares Q1 and M1 performance data with 2017 safety culture data and Q2 and M2 performance data with 2020 safety culture data. A majority of the KPIs are measured via WRPS protocols and activities with limited external influence (i.e., internal authority). Two of the KPIs, *Environmental Notifications - Planned Outages & Other Notifications* and *Self-Identified Issues - Externally-Identified*, are monitored by WRPS based on DOE, and federal, state or local agency requirements and regulations (i.e., external authority).

Descriptive statistics, to include standard deviations, averages, and means, of the organizational performance measures, are provided in Table 5 for the quarterly data and Table 6 for the monthly data. Brief descriptions of each organizational measure follow:

- *Days Away, Restricted, Transferred Case Rate (DART)* represents a count of injuries that require time away from regular work duties.
- *Total Recordable Case (TRC) Rate* is the count of injuries that meet the threshold of "Recordable Cases" which is defined by OSHA as "Any work-related injury or illness requiring medical treatment beyond first aid."
- *First Aid Case Rate* is a count of minor injuries requiring no further care (i.e., below the threshold of DART and TRC injuries).
- *Stop Works Issued* is a count of Stop Works issued for safety concerns; all workers can initiate Stop Works, and there is no performance "goal."
- *Medical Appointment No-Shows* is a count of scheduled medical appointments to which workers did not complete, and associated billing. This is a cost tracking tool, not a safety performance metric.
- *Regulatory Notices of Correction / Violation (Number of Inspections)* is a count of notices and violations resulting from regulatory oversight inspections.
- *Environmental Notifications (Planned Outages & Other Notifications)* monitors notifications to regulatory agencies as required by environmental permits or regulations for Air, Resource Conservation and Recovery Act, Water, and Spills.
- *Potentially Contaminated Liquid Contact* is a subset of overall Radiological Contamination Events. Reportable occurrences involve loss of control of radioactive material that exceeds the relevant DOE ORPS reporting criteria. Non-reportable events are considered leading indicators, which may precede more serious contamination control issues. The Radiological Contamination data is tracked on a quarterly basis.
- *Radiological Control (RadCon) Adherence Deficiencies* is a subset of overall Radiological Contamination Events. The Radiological Contamination data is tracked on a quarterly basis.
- *Contamination Discovery Events* is a subset of overall Radiological Contamination Events. The Radiological Contamination data is tracked on a quarterly basis.
- *Radiological Containment Deficiencies* is a subset of overall Radiological Contamination Events, which includes both reportable and non-reportable events. The Radiological Contamination data is tracked on a quarterly basis.
- *Total Contamination Events* is a subset of overall Radiological Contamination Events, which includes both reportable and non-reportable events. The Radiological Contamination data is tracked on a quarterly basis.
- *Self-Revealing Issues* is a subset of the Self-Identified Issues metric, which tracks the percentage of self-identified issues in comparison to externally identified and self-identified issues. Self-Revealing issues are events that are significant and real-time (e.g., pipe break, valve failure, loss of power, injury, natural disaster) that are immediately apparent.
- *Externally Identified issues* is a subset of the Self-Identified Issues metric. Externally Identified issues are issues identified by others, generally oversight entities, to include DOE, and federal, state or local agencies.
- *Self-Identified issues* are issues that are identified by processes controlled by the contractor. These include assessments and observations sponsored or subcontracted by the contractor. The performance goal is for the majority of issues in the system to be self-identified.
- *Emergency Preparedness Evaluated Drill Performance (Average Drill Score)* is a measure of the quality (score) of performance of drills (fire drills, suspicious package, injuries, etc.).
- *Operations Drill Activity* is used to ensure sufficient drills are conducted to maintain personnel proficient in their response to abnormal/upset/off-normal conditions and equipment failures.
- *Evaluations Completed* is a subset of the Issue Evaluation Timeliness metric, which tracks completion of steps within the issues management process to ensure timely correction.
- *Pending Evaluations* is a subset of the Issue Evaluation Timeliness metric, which tracks evaluations that are pending.
- *Average Age of Pending Evaluations* is a subset of the Issue Evaluation Timeliness metric which tracks the aging' of pending evaluations.

Table 8
Regression statistics for the safety culture factors and monthly performance measures in 2017 and 2020 – Set A.

	B		C		D		E		F		G		H		I		J		K		L		M	
	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20
F1	−0.236	−0.253	−0.732	−1.056*	−2.454	3.106	0.996	0.200	−9.312	5.700	−1.968	0.544	−1.011	−0.834	3.641	0.123	−7.852	12.447	−59.977*	4.713	−0.080	−0.561*	2.625	0.517
F2	−0.479*	−0.106	−0.554	−0.186	−1.260	−0.022	0.775	−0.587	−19.558	−13.741*	1.446	−1.349	0.667	−0.112	−1.602	0.802	−2.166	−4.646	15.286	−7.149	0.027	0.214	−0.894	−1.464
F3	0.109	0.156	0.038	0.450	1.056	0.239	−1.659	−0.867	−7.608	2.848	−0.729	0.569	−6.587*	−0.375	−4.774	−3.331*	15.582	−1.673	49.019	−35.137	0.051	0.217	−3.152	−2.559
F4	0.141	0.092	0.553	0.508	1.465	−2.133	0.319	1.193	15.838	−3.577	1.523	−0.560	3.063	1.281	1.956	5.498**	−9.285	−3.693	1.776	41.907	0.042	0.086	1.387	2.252
Standard Error	0.303	0.266	0.501	0.556	3.133	2.577	1.709	1.658	20.630	11.040	1.883	1.574	3.788	1.045	3.267	2.615	13.760	10.200	37.000	38.040	0.242	0.259	5.177	2.626
R-Squared	0.429	0.127	0.397	0.267	0.090	0.131	0.118	0.066	0.291	0.208	0.225	0.129	0.434	0.124	0.393	0.446	0.222	0.120	0.378	0.138	0.032	0.274	0.107	0.141
Adjusted R-Squared	0.286	−0.025	0.247	0.140	−0.138	−0.020	−0.103	−0.097	0.113	0.071	0.032	−0.023	0.293	−0.029	0.241	0.350	0.028	−0.034	0.222	−0.012	−0.226	0.128	−0.117	−0.008
F Statistic	3.007	0.838	2.637	2.096	0.394	0.867	0.534	0.405	1.639	1.513	1.163	0.850	3.071 *	0.810	2.587	4.637**	1.143	0.780	2.430	0.918	0.125	1.882	0.477	0.945

*p < 0.05; **p < 0.01; ***p < 0.001.

Table 9
Regression statistics for the safety culture factors and monthly performance measures in 2017 and 2020 – Set B.

	N		O		P		Q		R		S		T		U		V		W		X		Y	
	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20
F1	−6.491	18.380	30.520	2.630	8.693	−3.846	−0.041	0.026	−31.011	46.351	−56.295*	14.190	−42.730	29.790	−4.739	1.399	−3.736	0.432	−0.104	−0.038	0.007	0.023	−0.015	0.015
F2	4.784	−15.740	10.440	−2.776	−6.282	3.205	−0.022	−0.008	13.208	−7.944	−4.013	−17.440	18.340	−12.090	−4.738	−1.168	−6.758	−1.800	−0.041	0.070	−0.006	−0.024	0.001	−0.014
F3	30.985	−22.580	−8.140	−27.695	0.510	0.699	0.024	0.018	11.959	−23.236	46.259	−32.890*	49.740	−152.910*	−6.355	4.456	−0.880	6.956	0.104	−0.112	0.014	−0.022	0.021	−0.032
F4	−26.871	24.070	−24.850	32.434	0.130	0.432	0.004	−0.027	1.732	−1.325	26.373	22.650	−13.770	123.280	5.933	−7.939	6.079	−11.239*	0.020	0.118	−0.018	0.027	−0.009	0.038
Standard Error	25.340	38.950	27.040	46.420	6.965	3.560	0.048	0.034	31.910	43.210	32.240	26.840	42.320	97.390	9.469	8.765	7.923	6.795	0.071	0.160	0.052	0.048	0.050	0.059
R-Squared	0.293	0.087	0.179	0.062	0.425	0.139	0.157	0.135	0.186	0.095	0.429	0.185	0.301	0.255	0.281	0.103	0.216	0.311	0.285	0.114	0.023	0.089	0.038	0.066
Adjusted R-Squared	0.116	−0.072	−0.026	−0.102	0.282	−0.011	−0.054	−0.016	−0.017	−0.062	0.287	0.043	0.126	0.125	0.101	−0.054	0.020	0.191	0.106	−0.040	−0.221	−0.069	−0.202	−0.096
F Statistic	1.655	0.548	0.872	0.378	2.960	0.929	0.746	0.894	0.915	0.605	3.009*	1.303	1.722	1.968	1.560	0.657	1.102	2.594	1.593	0.742	0.095	0.563	0.159	0.409

*p < 0.05; **p < 0.01; ***p < 0.001.

Table 10
Regression statistics for the safety culture factors and quarterly performance measures in 2017 and 2020 – Set A.

	A		B		C		D		E		F		G
	17	20	17	20	17	20	17	20	17	20	17	20	17
F1	−0.496	−0.549	−0.083	0.218	0.227	−9.324	−2.939	1.396	−32.470	−120.785	5.003*	1.345	−4.664
F2	−0.273	−0.138	−0.221	−0.777	−3.042	−0.098	−1.751	−1.663	−40.650	−2.772	−5.906*	0.529	4.747
F3	0.319	−0.666	0.470	−2.520	2.546	9.131	−2.574	5.885	−66.130	78.325	−1.327	1.250	−11.419
F4	0.040	1.255	−0.302	2.310	−6.835	−1.164	6.515	−8.493	65.030	25.914	2.995	−4.737	8.147
Standard Error	0.689	0.479	1.528	1.050	6.773	3.543	4.001	3.083	54.710	30.290	0.828	1.227	9.593
R-Squared	0.335	0.410	0.039	0.538	0.521	0.422	0.527	0.588	0.710	0.455	0.975	0.670	0.452
Adjusted R-Squared	−0.994	−0.181	−1.883	0.076	−0.438	−0.156	−0.418	0.176	0.131	−0.090	0.924	0.340	−0.643
F Statistic	0.252	0.694	0.020	1.165	0.543	0.730	0.558	1.426	1.226	0.835	19.210	2.028	0.413

*p < 0.05; **p < 0.01; ***p < 0.001.

- *Percentage 45-Days Old* is a subset of the Issue Evaluation Timeliness metric, which tracks the ratio of 'aging' action requests.
- *Action Requests (ARs) Initiated* is a subset of the Issue Resolution Timeliness metric, which tracks the rate of issues (action requests) submitted to the issues management system.
- *Condition Report (CR) Corrective Action Extensions* is a subset of the Issue Resolution Timeliness metric, which tracks completion of issues within the issues management process to ensure timely correction of conditions.
- *Open CRs (Backlog)* is a subset of the Issue Resolution Timeliness metric, which tracks completion of issues within the issues management process to ensure timely correction.
- *Average Age of Open CRs* is a subset of the Issue Resolution Timeliness metric.
- *Issue Resolution Timeliness Index* is a subset of the Issue Resolution Timeliness metric.
- *Management Observation Program (MOP) Worksite Visit (WSV) Participation (Senior Management Participation)* is a count of participation by managers that either directly report to the company president, or who have only one manager between them and the president.
- *MOP WSV Participation (Level 2&3 Management Participation)* is a count of mid-level management participation per month.
- *MOP WSV Participation (Overall Participation)* is a count of participation in the MOP and WSV by supervisors and individual contributors.

3. Results

3.1. Safety culture factor analysis

Results from both the 2017 EFA and 2020 EFA indicate that multiple safety culture traits are correlated, and that a 4-factor model better fits the data than a 10-factor model. Confirmatory factor analyses (CFA) further confirmed that each item had statistically significant factor loadings for the 4-factor model. All correlations for both the 2017 and 2020 datasets were significant at the 0.001 level. Using these results, the ten safety culture traits were combined into four new factors - Decision Making & Work Processes, Personal Accountability & Questioning Attitude, Respectful Work Environment & Environment for Raising Concerns, and Leadership Safety Values and Actions & Effective Safety Communication – which will be referred to as Safety Culture Factors 1–4, respectively and are presented in Table 7.

Each of the four safety culture factors improved between 2017 and 2020. The percent differences ranged from 0.4% to 2.3%. There were statistically significant positive changes for two of the factors between 2017 and 2020: Decision Making & Work Processes ($p < 0.0001$) and Leadership Safety Values and Actions & Effective Safety Communication ($p < 0.05$). In addition, a statistically significant positive change was found for the overall safety culture measure (combining all safety culture factors) at the $p < 0.05$ level.

3.2. Correlation analysis

Independent correlation matrices for the 2017 and 2020 performance measures were constructed to explore the relationships between the metrics. There were strong positive and negative correlations among various safety performance parameters. The correlations for the monthly data ranged from −0.79 to 0.98. There were correlations significantly different from zero for 140 values (12%). The performance measure with the most statistically significant correlations was *Issue Resolution Timeliness – Action Requests Initiated* with seven and eight significant correlations in 2017 and 2020, respectively. The correlations between *Management Observation Program – Worksite Visit Participation – Level 2&3 Management* and *Management Observation Program – Worksite Visit Participation – Overall Participation* resulted in the highest values of 0.96 and 0.98 for the 2017 and 2020 data, respectively. These results imply that the *Issue Resolution Timeliness – Action Requests Initiated* measure may serve as a stronger predictor of organizational performance given the moderate to strong positive relationships with other monthly measures.

The correlations for the quarterly data ranged from −0.92 to 0.98. There were correlations significantly different from zero for 120 values (7%). The performance measure with the most statistically significant correlations was *Issue Evaluation Timeliness – Evaluations Completed* with three and ten significant correlations in 2017 and 2020, respectively. The correlations between *MOP WSV Participation – Level 2&3 Management* and *MOP Overall Participation* resulted in the highest values of 0.98 and 0.97 for the 2017 and 2020 data, respectively. These results suggest that the moderate to strong correlations for the *Issue Evaluation Timeliness – Evaluations Completed* measure in both positive and negative directions may indicate unique effects between safety issue evaluation actions and safety performance.

Correlations were calculated between each performance measure and the four safety culture factors. The correlations for the monthly data ranged from −0.62 to 0.55. For the monthly data, there were correlations significantly different from zero for 12 values (6%). Significant correlations for both 2017 and 2020 were calculated between *Medical Appointment No-Shows - Total No-Shows* and Safety Culture Factor 2 (Accountability & Questioning Attitude) at −0.47 and −0.39, respectively. Some survey comments suggested that when WRPS workers miss on-site medical appointments, it may be attributed to a lack of communication by the supervisor (failure to remind) or schedule pressure.

The correlations for the quarterly data ranged from −0.82 to 0.74. For the quarterly data, there were correlations significantly different from zero for 5 values (2%). The quarterly performance measures with the most statistically significant correlations were *Regulatory Notices of Correction / Violation - Number of Inspections*, *Self-Identified Issues - Self-Revealing, Operations Drill Activity*, *Issue Evaluation Timeliness – Avg. Age of Pending Evaluations*, and *Issue Resolution Timeliness – Open CRs (Backlog)* with one significant correlation each.

G	H		I		J		K		L		M		N		O	
20	17	20	17	20	17	20	17	20	17	20	17	20	17	20	17	20
−1.000	−1.537	−0.802	−0.095	−4.785	−2.127	−1.299	0.211	−2.229	−3.547	−9.115	−16.659***	41.247	45.095	−69.605	214.334	113.500
−2.403*	−0.378	0.355	−0.533	0.985	1.428	0.665	−1.943	−0.023	−1.426	1.981	2.026*	−7.319	−49.046	−3.684	−151.393	−163.900
−0.948	0.886	−0.676	1.443	0.554	−0.479	2.786	3.452	1.335	5.302	3.999	−2.221*	−9.591	−0.140	83.914*	−84.176**	218.600
3.461*	0.751	0.857	−0.492	2.645	2.512	−3.215	−2.062	0.737	0.709	1.023	10.566***	−25.363	0.836	−25.572	−10.773	−222.800
0.546	1.134	0.561	1.761	2.650	1.176	1.316	1.182	0.442	1.637	2.810	0.219	6.423	40.840	17.190	4.077	71.040
0.884	0.471	0.370	0.225	0.122	0.716	0.567	0.783	0.498	0.841	0.395	1.000	0.581	0.434	0.745	0.999	0.773
0.767	−0.588	−0.261	−1.325	−0.756	0.146	0.135	0.348	−0.004	0.523	−0.210	0.999	0.161	−0.700	0.491	0.997	0.545
7.589*	0.444	0.587	0.145	0.139	1.257	1.311	1.800	0.993	2.647	0.653	1431.0***	1.385	0.383	2.925	514.0**	3.398

3.3. Regression analysis

Results of the regression of the safety culture factors against the monthly performance measures are presented in Tables 8 and 9. The results reveal fifteen significant relationships between the safety culture factors and various performance measures. The performance measure with the most statistically significant results ($n = 3$) was *Self-Identified Issues - Self-Revealing*, which was significantly associated with Factor 3 and Factor 4 along with the overall F statistic. Safety Culture Factor 3 (Respectful Work Environment & Environment for Raising Concerns) showed a significant ($p < 0.05$) negative linear relationship with the *Self-Identified Issues - Self-Revealing* parameter for 2020. This finding suggests that, as the work environment improved in regard to trust and fewer incidents of retaliation, there was a reduction in the number of unpredictable site events. Between 2017 and 2020, WRPS implemented safety books to improve efficiency in addressing minor safety issues and several other initiatives to improve trust and reduce retaliation, to include new manager training improvements, Speak Up Listen Up (SULU) training, a new position devoted to leadership development, and the Good Catch program (Wallace et al., 2017). These initiatives were noted in the survey comments as contributors to the improved safety culture. Because a majority of the WRPS self-revealing events are not natural disasters, there is a greater likelihood of preventing them through an emphasis on routine and comprehensive maintenance. This result illustrates that when employees are able to raise concerns using formal and informal channels and those raised concerns are acknowledged and addressed by leadership, organizations are better able to prioritize regular repairs to critical systems that prevent events which lead to work stoppages, emergency solutions, and significant schedule impacts (Martin et al., 2018).

Safety Culture Factor 4 (Leadership Safety Values and Actions & Effective Safety Communication) showed a significant ($p < 0.01$) positive linear relationship with the *Self-Identified Issues - Self-Revealing* parameter for 2020. As the leaders become more engaged in safety decisions, this finding implies an increase in the number of unpredictable site events. The majority of the survey questions that examine leadership focus on executive and organizational leadership, not supervisors and first-line managers. Therefore, as senior leaders become more involved in the day-to-day safety communications and actions, there is a higher likelihood of more self-revealing events since management visits can be perceived as a distraction if the visiting manager is not "imbedded" or has an office in the work environment. Survey comments suggest that when senior leaders visit the work areas to observe worker performance, these occurrences often drive unusual changes to the work flow where a greater emphasis is placed on organizing the work areas and providing a favorable experience for the executive observer. Although a majority of workers want to interact with executives and express their concerns, they do not want this opportunity presented in an artificial manner where all the preparations for the executive visit lead to work distractions and an overemphasis on visual appearance. Also, there is a potential for high-risk exposure when senior leaders visit the work areas because they are too removed from the work or potentially lack experience with the work.

Another explanation for the positive relationship between Safety Culture Factor 4 and *the Self-Identified Issues - Self-Revealing* parameter is that when leaders are engaged in healthy safety behaviors and prioritize safety communication as a core value, trust in senior management is increased among the workforce and can lead to complacency among employees. Research has shown that when senior management is considered trustworthy and committed to ensuring that all work will be conducted in a safe manner, workers may exhibit a more complacent attitude (Schopf et al., 2021). As such, workers may less proactive about addressing routine maintenance and noticing leading indicators of an impending event. This finding serves as a reminder that strong safety leadership works best when it empowers employees to take ownership for addressing issues instead of leaders solving all the concerns for employees without their involvement and engagement.

Results of the regression of the safety culture factors against the quarterly performance measures are presented in Tables 10 and 11. The results reveal twenty-five significant relationships between the safety culture factors and various performance measures. The performance measures with the most statistically significant results were *Self-Identified Issues - Self-Revealing* ($n = 5$), *Operations Drill Activity* ($n = 5$), and *Self-Identified Issues - Self-Identified* ($n = 4$). The *Self-Identified Issues - Self-Revealing* and *Operations Drill Activity* measures were significantly associated with all four safety culture factors along with the overall F statistic. The *Self-Identified Issues - Self-Identified* measure was significantly associated with all safety culture factors, except for Safety Culture Factor 4 (*Leadership Safety Values and Actions & Effective Safety Communication*), along with the overall F statistic.

Safety Culture Factors 1 and 3 showed a significant ($P < 0.001$ and < 0.05, respectively) negative linear relationships with the *Self-Identified Issues - Self-Revealing* parameter for 2017. As organizations make improvements in the work and decision making processes that govern the safe execution of work and reinforce positive work climate expectations that convey respect and trust of the workforce, this finding suggests a correlating decrease in the number of unexpected site events. The key discriminator for developing this type of positive work environment and culture is employee empowerment rather than transactional leadership. Bian et al. (2019) found that employee empowerment positively predicted employees' safety behaviors and served as an effective mediator to improve employee behavior under a transactional leadership environment. Between 2017 and 2020, WRPS chartered several dedicated working groups in which employees are able to contribute to the decision processes for safety concern response implementation. These findings imply that unexpected, negative work events can be prevented when employees are empowered to voice concerns and encouraged to participate in the decision-making process to plan shutdowns for repairs, prioritize maintenance tasks, and serve on cross-functional teams to address wide scale safety concerns.

Safety Culture Factors 2 and 4 showed a significant ($P < 0.05$ and < 0.001, respectively) positive linear relationships with the *Self-Identified*

Table 11
Regression statistics for the safety culture factors and quarterly performance measures in 2017 and 2020 – Set B.

	P		Q		R		S		T		U		V
	17	20	17	20	17	20	17	20	17	20	17	20	17
F1	−0.094	0.541	−5.056*	14.910	116.950	151.240	18.973	−177.900	−54.030	−5.566	0.066	−0.002	194.080
F2	0.100	0.029	14.922**	−10.003	10.080	−138.950	−1.421	−206.470*	−6.697	−12.226	−0.043	0.035	−99.790
F3	0.043	−0.658	5.878*	−9.885	−64.500	83.140	−121.15	393.780*	30.084	−5.015	−0.007	−0.002	−117.860
F4	−0.100	0.201	−17.431**	−2.180	−20.480	−128.020	98.070	−77.430	1.160	20.757	0.004	−0.008	21.380
Standard Error	0.061	0.278	0.705	3.615	46.240	98.350	74.970	71.400	19.550	8.791	0.047	0.028	63.980
R-Squared	0.802	0.404	0.998	0.777	0.740	0.428	0.510	0.849	0.816	0.445	0.526	0.367	0.777
Adjusted R-Squared	0.407	−0.192	0.994	0.553	0.221	−0.144	−0.469	0.699	0.447	−0.110	−0.421	−0.267	0.330
F Statistic	2.029	0.679	235.2**	3.477	1.425	0.749	0.521	5.634	2.212	0.802	0.556	0.579	1.739

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Issues - Self-Revealing parameter for 2017. Efforts to promote greater accountability and questioning attitude among employees along with leadership involvement and communication around the safe conduct of work may lead to an increase in the number of unanticipated work site events. In many work environments, it is a challenge to hold all employees accountable for work behaviors in a consistent manner without accusations of retaliation and retribution. This finding seems to suggest that as organizations increase expectations around holding employees accountable, displaying a questioning attitude, and communicating those expectations that there may be self-imposed pressure among employees to focus on self-preservation and less on team performance. This potential degradation in teamwork may result in some negative consequences in catching the warning signs of a critical safety event due to less collaboration among work teams and decreased cooperation between work groups that belong to different departments or divisions. WRPS survey commenters noted that, in the past, accountability has sometimes been unevenly applied due to union involvement, favoritism, lack of visibility (back shift operations), and lack of management skill and discretion on reinforcing work team expectations.

Safety Culture Factors 1 and 4 showed a significant ($P < 0.05$ and < 0.01, respectively) negative linear relationship with the *Operations Drill Activity* parameter for 2017. Safety Culture Factors 2 and 3 showed a significant ($P < 0.01$ and < 0.05, respectively) positive linear relationship with the *Operations Drill Activity* parameter for 2017. Operations Drills are employed within organizations to train employees on the proper response to unusual conditions and equipment failures and are positively associated with improved employee perceptions around accountability, trust, and respect. This finding seems to suggest that operational drills convey a message to the workforce that the organization cares about individual employee safety more than profits or schedule demands through the intentional choice to pause the normal operation of work to conduct drills. However, if too many drills are held or if they are conducted in a way that does not convey confidence in an appropriate emergency response, these findings suggest that the drill may work against efforts to improve decision making, work processes, and leadership trust. Feedback from the WRPS survey comments indicated that the WRPS drills are rigorous, focus on continuous improvement, and are a constructive experience for employees.

Safety Culture Factors 2 and 3 showed a significant ($P < 0.001$ and < 0.01, respectively) negative linear relationship with the *Self-Identified Issues - Self-Identified* parameter for 2017. Safety Culture Factor 1 showed a significant ($P < 0.001$) positive linear relationship with the *Self-Identified Issues - Self-Identified* parameter for 2017. As the number of self-identified issues increases, there is an associated decrease in perceptions around workplace culture related to accountability, questioning attitude, respect, and trust.

This finding may be connected to how the issues and the response to the issues are communicated to the workforce. Self-identified issues can serve as an opportunity for continuous improvement and healthy performance enhancement. However, if rewards and incentives are attached to identifying issues, this parameter could result in perceived distrust among employees under the scenario that some employees receive recognition and accolades at the expense of others (Ghodrati et al., 2018). WRPS survey comments indicated that safety issue reports issued by an individual in one department have been used as a retaliation tool against other departments. These results also imply that enhancements in work planning and decision- making processes have a positive impact on the self-identification of issues.

4. Discussion

Previous research has shown correlation between safety culture and safety performance metrics with an understanding that the relationship between safety culture and safety performance is highly dependent on how and when both safety culture and safety performance are measured (Morrow et al., 2014). To characterize the relationships between safety culture and safety performance, the current study used factor analysis, correlations, and regression analyses to examine the relationships between safety culture factors and performance metrics for a nuclear waste cleanup operator. Support was found for the study's hypothesis linking safety culture to organizational safety performance. However, in some cases, improvements in safety culture resulted in decreased safety performance, indicating that safety culture activities (i.e., training, management observations) that are applied too intensely or in a regimented fashion may impede safety performance. This finding highlights the importance of using a mixed methods approach to evaluating safety culture rather than exclusively using survey data.

Churruca et al. (2021) found that qualitative and mixed methods approaches enhanced researchers' ability to assess aspects of safety culture beyond the applied survey dimensions that may lead to the discovery of unique associations or unexpected data connections. They conclude that such insights may provide a better understanding of culture on a micro-level and how to improve safety performance.

Because of the low occurrences of injuries and first-aid events at WRPS, it was necessary to identify alternative organizational safety outcomes for use as variables for the analysis. There is not a single organizational metric which corresponds to overall organizational performance or can be used as a measure of safety culture (Kalteh et al., 2021). Hence, organizational metrics should be taken in aggregate. The current study used 29 organizational metrics in the analysis and a vast majority of the metrics did not produce significant results. Clarke (2006) identified similar concerns with using a variety of safety performance measures to investigate the factors that comprise the concept of safety culture in the nuclear power industry. Clarke notes that variability in results may occur depending on how safety performance metrics are measured and the specific safety performance measures used in the analysis. In the current study, the metrics used to characterize the organizational performance were predominately internal measures, which lends these data to greater subjectivity.

Karanikas (2016) investigated the usefulness and applicability of various performance measurements in assessing organizational performance in relation to safety and other business goals. The study found

V	W		X		Y		Z		AA		BB		CC	
20	17	20	17	20	17	20	17	20	17	20	17	20	17	20
−141.2	62.980	−58.110	349.15*	249.9	−8.563	−17.760	−7.387	0.094	0.048	0.238	0.017	0.007	0.036	0.032
−99.060	−82.480	18.160	−51.080	−579.5	−0.234	6.038	−6.750	13.147	0.008	−0.107	0.036	−0.008	0.030	−0.019
340.130	194.390	44.760	−18.900	248.1	1.863	−12.916	10.985	−12.935	−0.008	−0.092	0.047	0.031	0.032	0.015
−127.2	−174.14	−48.0	−194.21*	−289.8	2.127	26.758*	−1.606	−0.140	−0.063	−0.072	−0.079*	−0.029	−0.078	−0.031
98.650	95.180	86.340	34.980	289.0	8.216	4.459	4.067	6.209	0.025	0.111	0.015	0.032	0.019	0.039
0.622	0.671	0.163	0.974	0.631	0.380	0.805	0.820	0.615	0.766	0.230	0.933	0.156	0.897	0.110
0.244	0.013	−0.673	0.923	0.262	−0.860	0.610	0.461	0.229	0.297	−0.540	0.798	−0.688	0.690	−0.781
1.644	1.020	0.195	18.990	1.710	0.306	4.130	2.281	1.594	1.634	0.299	6.912	0.185	4.340	0.123

that any measurement could be "variously interpreted either by different organizations or by departments and units within an organization, depending on their culture, knowledge and experience in safety management." Therefore, when collecting and applying organizational performance data for research purposes, the inclusion of diverse viewpoints, including safety professionals, nuclear workers, line management, and external regulators, is germane to the development and collection of sound and defensible conclusions. In this study, the authors did not investigate the approaches used by WRPS to identify and collect the organizational performance data. Future exploration opportunities exist in the area of working with organizational leaders to develop guidelines for collecting organizational performance metric data that is designed for research purposes to better understand and characterize nuclear safety concerns and issues.

Furthermore, the study by Karanikas also found that greater statistical utility may be achieved when research emphasizes weighing performance metrics with respect to their contribution to organizational safety. However, the study notes the difficulties associated with deciding the weight of each metric and establishing comparable weights across multiple organizations and within specific industries (i.e., safety issues response timeliness may be ranked as more important than the number of stop works issued, or the opposite). A valid and common approach, based on scholarly data, would be needed to develop and apply a weighing system to organizational performance metrics for correlation to nuclear safety culture data. This may be achievable within the DOE enterprise where managing contractors execute their performance missions within a collective safety framework and set of nuclear facility safety directives (Frias et al., 2020).

4.1. Limitations

Lastly, unique challenges were faced in conducting this research and analysis. Both the organizational safety performance data and safety culture data were held as proprietary data and, as such, could not be shared without use of either a non-disclosure agreement or submittal of data to the public release process, neither of which was feasible. This resulted in data sets being developed and analyzed without direct context, since raw data could not be shared between organizations.

4.2. Conclusions

Based on the results of this study, we conclude that significant relationships between safety culture and performance measurement variables were demonstrated for a nuclear waste contractor. Previous nuclear facility safety studies have focused on the relationships between safety culture, outcomes related to personal safety, and outcomes that affect overall operational performance, independently. This study addresses a gap in the literature by looking at both sets of performance metrics simultaneously. Results from this study show that a combination of personal safety and operational performance measures served as the strongest predictors of improved safety culture. The performance measures with the strongest associations to a healthier safety culture were metrics related to the evaluation and resolution of safety concerns, the recognition and accurate categorization of self-revealing and self-identified issues, and drill activity. This observation highlights the importance of using a wide range of organizational performance data as inputs when developing action plans to improve a facility's safety culture since there are many indirect linkages between safety, quality, cost savings, and operation performance outcomes.

This study also showed that the strength and direction of the relationships between safety culture and organizational performance are highly variable and influenced by the robustness of the performance measurements. The need to collect high-quality, unbiased organizational performance data in conjunction with safety culture data is paramount to continuing this research and extending it to similar organizations. Therefore, the authors suggest targeted research to characterize the primary factors that influence how performance metrics are identified and collected within nuclear facilities to advance the degree and breadth of comparisons to safety culture data, including qualitative data, in future studies.

CRediT authorship contribution statement

Davyda M. Hammond: Project administration, Methodology, Investigation, Data curation, Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Adrienne L. King:** Methodology, Investigation, Data curation, Conceptualization, Writing – original draft, Writing – review & editing. **Margaux Joe:** Validation, Software, Investigation, Formal analysis, Data curation. **Jeffrey R. Miller:** Supervision, Data curation, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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