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An Analysis of the Effectiveness of Checklists when combined with Other Processes, Methods and Tools to Reduce Risk in High Hazard Activities

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Abstract – **Boeing pilots and other aviators in flight operations have used checklists for more than 75 years. Surgeons, astronauts, and other professionals have adopted checklists for routine situations. Boeing lab personnel use checklists to safely and accurately perform critical processes. Incorporating checklists in high hazard environments has been one of the most influential innovations to enhance safety. Using critical checklists, a specific application of checklists defined in this paper, could provide a safety interface between high hazard processes and potentially devastating results. This paper examines the use of checklists in various high risk environments, and pre- and post-checklist implementation comparisons.**

We will also discuss human factors studies that form the foundation for the use of checklists. We will draw parallels between what implementation teams in other fields have discovered when integrating checklists and the positive impact checklists can have on safety at Boeing.

The issues examined and conclusions documented here can be used to support the development of critical checklists in any industrial application.

Index Terms – **Checklist, critical checklist, high-hazard activities, high-risk behaviors, safety.**

I. Introduction

The term checklist is used in so many ways today that talking of "critical" checklists does not leave much of an impression. The following categories are indicative of the multiple uses of checklists. Each of these different uses has a particular purpose, and each has value and meaning as intended. But the type of checklist we want to consider in this paper has dramatic differences. The categories of checklists include:

Procedural checklists: Excessively long, complex, or critical tasks performed only occasionally require "read-and-do" checklists (those checklists not done from memory, but the checklist is read and the various tasks performed sequentially) to ensure specific tasks in both normal and non-normal situations are accomplished.

Preparation checklists: Multiple-step situations require checklists to ensure all of the variables are performed as desired; e.g. shopping lists, long-distance trip or backpacking planning, group or individual communication sessions.

Problem-solving checklists: Multiple-point, question type checklists used for troubleshooting complex procedures or tasks to pinpoint what went wrong, areas of difficulty, or solutions to barriers blocking forward movement.

Prevention checklists: Critical checklists address errors, mistakes, mishaps in high-hazard work areas that can result in injury or death to users or neighbors, destruction of property, or impact to reputation or continued business success.

Our primary focus in this paper is to examine the effectiveness of prevention checklists in industries such as medicine, aviation, and nuclear power where high-risk is a daily occurrence. At the same time, we will comment on the use of checklists in other industries such as mining and rail transportation where they have been proven effective for other purposes.

The emphasis on safety at Boeing can capitalize on all of these various categories of checklists to help us move our effective incident rate to zero. By tapping into the potential in our work areas where these various categories of checklists could be used, we can greatly increase success rates.

The initial motivation for the work highlighted in this paper was to demonstrate that checklists can be useful to reduce risk in high-hazard areas whether that is in the lab, test facility, flight line, or on the production floor. However, the results of this effort underscore the point that checklists are most effective when implemented as part of an overall safety campaign to increase awareness and build a culture of safety.

While the use of checklists is present in almost every industry, extensive studies examining their effectiveness and the science of how to develop effective checklists are almost non-existent except in the medical field, nuclear power, and the aviation industry. As a consequence, more of our findings are from those three fields with supportive findings from other fields.

In each industry we will examine factors that led up to the implementation of checklists; the cause, what processes were followed to make them a daily reality; and what were the results and key points from these efforts.

II. Aviation

Cause: If there was a defining moment in the aviation industry when checklists became standard operating procedure that pilots were expected to use, it occurred in 1935.

The Army Air Corps was to award a contract for the next generation bomber, and three companies were bidding for the contract: The Douglas Aircraft Company with the Douglas DB-1, the Glenn L. Martin Company with the Martin 146, and Boeing with the Model 299. It was acknowledged that the Boeing four-engine plane with many new features was by far the better machine and the competition was purely academic. The Model 299 could fly farther, faster, and carry more payload than either of the other two entries.

However, during the demonstration trials the Boeing plane crashed and was destroyed, killing the two expert pilots and seriously injuring the engineers on board. This resulted in Boeing's disqualification. Boeing's internal investigation determined the pilots had made an error by not unlocking the wind gust-lock. The gust-lock, one of the new features added, is engaged while on the ground to prevent elevator damage from high-wind situations, but must be released prior to take-off. When the Model 299 took off with the gust-lock engaged the elevators were inoperable.

When the competition demonstration flights had to be re-run because of a technicality, Boeing reentered the Model 299 with only one alteration: Boeing experts developed a series of normal checklists for the pilots to use to ensure that critical tasks were accomplished. As a result, Boeing won the competition and more than 12,000 of what became the B- 17 Flying Fortress aircraft were sold.[1]

Since that day, the innovation of using checklists has been a mainstay for pilots and are mandated by the Federal Aviation Administration (FAA) and other regulators worldwide. This is as true for Boeing test pilots as it is for commercial airline pilots. Boeing test pilots use checklists routinely when flying test sequences to evaluate new aircraft, and they are dedicated to using these checklists because they know they can prevent human errors that could lead to catastrophe.

Another contribution from aviation to the field of checklists was the introduction of electronic checklists. These are to replace hundreds of paper checklists pilots carry on every flight. The Boeing Electronic Checklist system has been so successful at reducing errors that it will eventually become part of every airplane the company delivers.[2]

So an analysis of the effectiveness of checklists in aviation is not so much a determination of where they are used, or even if they are effective, but more an examination of whether they are still being used consistently, and how they can be improved. In fact, Dr. Key Dismukes, lead scientist at the NASA Ames Research Center, makes this statement, "Even though modern airlines operate at extremely high levels of safety, the very fact that the safety level is so high makes it difficult to detect when safety begins to erode."[3]

- According to the National Transportation Safety Board (NTSB), checklists and monitoring of cockpit equipment are two of the most crucial defenses against malfunctions and errors, yet failures in checklist use and monitoring have contributed to many aviation incidents.4
- The question in the aviation industry then becomes why do checklists and monitoring sometimes fail to catch errors and equipment malfunctions as intended with resulting accidents?5 The findings that address this question apply to any field where experienced and expert personnel perform critical tasks that are well-practiced and often performed from memory leading to repetitious responses.
- **Process:** Dr. Dismukes and his team wanted to find the answer to this question, and to do this they observed crew performance from the cockpit jumpseat during normal airline operations.6 The process of looking at ways to improve the use of checklists and reduce deviations from them included:
    - Acquiring more thorough data on the operational factors that influence crew performance using the line operational safety audits (LOSA) airlines already collect.
    - Exploring more explicit methods to train pilots to detect and isolate errors before they get out of hand.
    - Researching to understand the cognitive and perceptual processes that underlie human vulnerability to characteristic forms of error.
    - Proposing the design or redesign of equipment, tasks, procedures, and organizational policies and practices that start from the basic understanding the human users will make errors.[7]
- **Results:** These studies by Dr. Dismukes and others have identified four ways that aircraft flight crews deviate from the proper use of checklists contributing to their ineffectiveness. These include:
    - At times a crewmember simply does not do the checklist.
    - The crewmember may do the checklist but misses an item.
    - A crewmember responds to the call on the checklist as required but indicates it is checked or set, when in fact it is not checked or set.
    - The crew may start the checklist, but it is interrupted for some reason and not completed.[8]

These studies have also indicated several reasons why crewmembers deviate from the expected use of checklists, including:

Distractions: When interruptions come in any form and cause the crew to be distracted from the checklist, it is easy for them to get lost in the use of the checklist or for it to be completely forgotten since the external cues that initiate the checklist are missing or different.

Individualism: Pilots are individuals, and no matter how well-trained they are, they will exert individual influence on the use of checklists. The problem is that conflict arises between the expression of a pilot's individualism and the necessary standardization for proper use of a checklist.

Complacency: Pilots can become complacent by the inherent tolerance of the aviation system and the fact that most pilots in the day-to-day routine of flying face few emergencies or abnormal circumstances.

Humor: Some pilots like to add variety and humor into the otherwise boring and humorless atmosphere of the flight deck. However, adding humor by substituting non-standard callouts for the checklist requires the responder to make unnecessary interpretations during the high-risk operation of flight.

Frustration: When some routines of flight deck life prove to be frustrating, crewmembers will find ways to work around them. This may be seen by the crew using compromised flight patterns that are not in accord with checklists, adding complexity to their flying situation.[9]

Key Learning: Labs, test facilities, production and other industrial applications need to have the same level of dedication, and be as consistent in using checklists, as test pilots are to ensure that checklists can have the impact on the organization that they can have.

Key Points: Researchers provide perspective from analyzing real-time decisions and discoveries from aircraft observations and accidents when it comes to the use of checklists and the failure to catch errors. These include:

- The use of checklists will not eliminate all aircraft accidents. There are still accidents in which the studies show that the crew made decisions consistent with typical airline practice and still met disaster because risk cannot be completely eliminated.[10]
- Too often it is easy to simply blame the crew and ascribe blame with the finding of "pilot error." With the need to assign blame, it is much wiser in most cases to assign it to the inherent vulnerability of conscientious experts to make errors occasionally.[11]
- To improve aviation safety, it is critical that we shift from a perception where we find consolation in ascribing the prime cause of accidents to pilot errors, and move to thinking of errors as the consequence of many factors that combine to create conditions for accidents.[12]
- Aircraft accidents have occurred in the past where it was determined a misuse of checklists was a contributing factor. These accidents may have been avoided if more emphasis had been placed on the importance of checklist use and reminders of situations in which deviations from checklists occur or how they can be misused.[13]

It is crucial that performance evaluation and theoretical rhetoric proclaim the same message. When pilots are measured on their on-time performance record, reducing time allowed for turnarounds, and reducing fuel consumption, they understand these to be the airline's primary performance criteria. If pilots are expected to demonstrate proper checklist use or unstabilized approach call-outs, these need to be a part of their performance evaluation demonstrating the company's commitment to the use of checklists and safety.[14]

III. MEDICINE

Cause: While the medical field may not have had one defining moment when the checklist became a reality for medical practitioners, there were at least two influential events that spurred checklists into the limelight:

One was the central-line associated bloodstream infection (CLABSI) research conducted by Dr. Peter Pronovost, a physician at Johns Hopkins Hospital, that confronted the belief that CLABSI were inevitable infections and were simply a cost of being in the hospital.[15]

- The other was the introduction of the Surgical Safety Checklist by the World Health Organization (WHO) to address the issue of surgical complications and ensure basic minimum safety standards. Surgical complications include: wrong patient/procedure/site surgery, anesthesia equipment problems, lack of availability of necessary equipment, unanticipated blood loss, non-sterile equipment, and surgical items (e.g. sponges) left inside patients.

CLABSI: In the year 2000, the Institute of Medicine released a groundbreaking report, *To Err is Human: Building a Safer Health System,* that indicated 44,000 Americans die each year as a result of preventable medical errors, and the number may be as high as 98,000.[16] One other finding that has caught the attention of providers and payers of health care is hospital-acquired infections, the central line associated bloodstream infections Dr. Pronovost studied. Approximately 48 percent of all patients admitted to an ICU have a central line inserted and on average there are 5.3 central-line infections per 1,000 catheter days.[17]

That may not seem like a significant rate until you consider the associated statistics. When a patient develops a central-line associated bloodstream infection, the consequences are serious and expensive. The cost for treatment and prolonged hospitalization ranges from $2,000 to $3,000 per day, which amounts to an average cost of $45,000 per patient. And this treatment is not always successful, resulting in a mortality rate of approximately 18 percent.[18]

One researcher equates deaths resulting from medical care to be equivalent to three fully-loaded jumbo jets crashing every other day.[19] The Institute of Medicine reports that the total estimated cost of medical errors in the United States is $17-$29 billion per year.[20] In addition, the Centers for Disease

Control estimates that 10-20 percent of patients acquires some type of infection while in the hospital.[21] What this adds up to is an estimated 250,000 central-line infections each year in the United States leading to 30,000 deaths, and adding a cumulative cost of billions of dollars annually.[22] In fact, more people die of health-care associated infections each year in U.S. hospitals than from breast cancer, AIDs, and auto accidents combined.[23]

In 2001 Dr. Pronovost wanted to know why and what could be done about it.

Process: Dr. Pronovost and his team saw the necessity of incorporating much more than a simple checklist to try and address the CLABSI issue. Their perspective was that they needed to think about the entire care delivery process: how to deliver care, how to organize the systems for this purpose, and how to identify and fix broken or risky systems. Their hypothesis was that if they could do those things, improvements in patient safety and the quality of care would naturally follow.[24]

Their implementation plan designed to change the culture was called the Comprehensive Unit Based Safety Program (CUSP) and the CUSP implementation checklist included the following:

1. The initial step was to assess the safety culture of the organization where it was being implemented.
2. Then there was an educational component to increase the understanding of the science of safety.
3. The next stage was educating staff to identify problems.
4. Once staff members understood how to identify problem areas, they then needed to know how to resolve the problems.
5. There was also the necessity of bridging the gap between senior hospital leaders and frontline staff. To help address this they established a team leader, a physician champion, shift and ancillary staff representatives, and a senior executive to remove barriers, provide resources, and attend meetings.
6. Lastly, the team took steps to provide tools to improve teamwork, communication and other systems of care. These tools included a simple five-step checklist that focused on evidence-based procedures recommended by the Center for Disease Control (CDC). These five steps are hand hygiene, using full-barrier precautions during the insertion of central venous catheters, cleaning the skin with chlorhexidine, avoiding the femoral site when possible, and removing unnecessary catheters.[25]

Dr. Pronovost and his team first tested their ideas at their own hospital, Johns Hopkins. After working out the details for this implementation plan, they then went on to a much more extensive plan by launching CUSP in 103 intensive care units in Michigan, referred to as the Michigan Keystone ICU program.

Results: The initial results of the Johns Hopkins work were almost too good to believe, and Dr. Pronovost and his team were excited to see if those same results could be duplicated in a wider application in the Michigan hospitals.

- Johns Hopkins use of the CUSP plan evidenced the line infection rate go from 11 percent to zero. Over the following 15 months only two infections occurred, eliminating a projected 43 infections, eight deaths, while saving in excess of $2 million in just this one hospital. In four years, Johns Hopkins reduced CLABSI rates down to near-zero using the CUSP approach.[26]
- The Ozarks Medical Center, located in southern Missouri near the Arkansas border, implemented the CUSP plan and had not had a CLABSI in more than three years.[27]
- A Kansas project included more than 20 hospitals across the state saw CLABSI reduced by 69 percent.[28]

The Keystone program in Michigan saw CLABSI rates decrease by 66 percent, with a significant reduction in hospital mortality and a total savings of more than $200 million dollars and 150 lives.[29] [30] Before the Keystone program, the median rate of CLABSI in the associated hospitals was about three per 1,000 catheter hours, well above the national average. After 18 months using the CUSP plan, Michigan reported zero infections, has stayed that way for three years, and is now one of the nation's leaders in low infection rates.[31]

Key Learning: Checklists work most effectively when designed and implemented in the context of teams. This ensures that everyone has a part and is a contributor to both the checklist's development and its rollout.

Key Points: The following were observations and learnings mined from various successful implementations of the CUSP plan developed by the Pronovost team that have significant application to developing a checklist culture:

- "You have to get CUSP components ingrained in your culture until you can say this is just how we do work," stated Becky Miller, Executive Director of the Center for Patient Safety in Kansas City.[32]
- Mary Fine, RN and Director of Quality at Ozarks Medical Center affirmed, "Engaged leadership is essential to sustaining a culture of safety."[33]
- A survey of four typical community hospitals revealed that buy-in goes hand-in-hand with staff ownership—if staff members participate in the development and execution of the initiative, they are more apt to follow the guidelines and produce positive results.[34]
- The checklist is a tool that can assist with three key elements important to the surgical patient: improving teamwork and communication, increasing efficiency, and reducing complications.[35]
- Dr. Pronovost recognized sustainability requires a "complete culture change" that goes well beyond checklists and reminders to wash hands and use antiseptic. He goes on to say that the key to success is not just following standardized checklist steps but that hospitals also search for errors on a continuing basis, know their infection rates and continuously

monitor them, and give feedback to doctors and nurses so they know the science behind the checklist is valid. "The use of checklists is not the end-game," Pronovost says, "reduced infections are."[36]

Checklists are a good way of making certain that tasks get done, but determining the best way of proceeding in a complex health-care setting is not always straightforward. That's where expertise and experience comes in.[37]

The Keystone Michigan program was a complex, cultural and organizational change effort that was well grounded in theory, and the rejection of a command control regime where workers are simply told what to do (just given a checklist) and expected to go and do it. Instead, they are encouraged to develop their own checklist that fits their unique challenges and culture.[38]

WHO Surgical Safety Checklist: Surgical complications represent a significant cause of morbidity and mortality with the rate of major complications after inpatient surgery estimated at 3-17 percent in industrialized countries.[39] In 2008, the WHO undertook to develop a checklist to address this on-going issue. The WHO Surgical Safety Checklist was tested at eight different sites around the world, with a wide variance in the number of beds, the number of operating rooms, and the income level of the country. Since then, it has been introduced into more than 3,900 operating theaters in 122 countries.

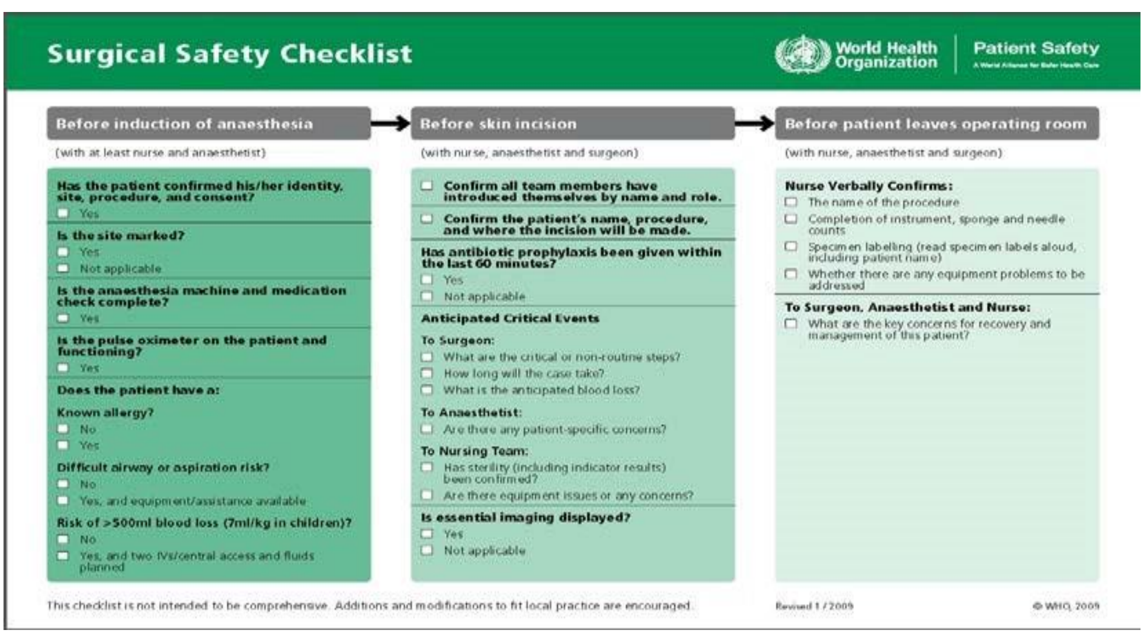
Process: Studies of the implementation of the WHO checklist show that success depended on several factors:

- Good training and staff understanding of why the checklist was being introduced as well as its use. Education took many forms including posters, hospital-wide publicity, training classes, pilot testing, and others.
- A local champion to encourage the use of the checklist and ensure that results were captured and that use of the checklist was a goal of all surgical teams.
- Support from upper management to demonstrate commitment to the process and the tool.
- The ability for users to modify the checklist to fit their unique needs and environment.
- Distribution of responsibility for completing, calling, and responding to the various items on the checklist.
- The feeling of ownership by team members and that they could have a positive impact on the safety of the patient. They also have ownership in the actual checklist by being able to provide feedback to improve the actual callouts used in rating each area.[41]
- A step-wise implantation process that incorporated real-time feedback and enhanced communication and teamwork.[42]
- Avoiding redundancy with existing systems for collecting information or rating surgical procedures or patient care.[43]

Results: A wide variety of results were recorded as the WHO checklist was implemented in various healthcare systems, cultures, and operating venues. These include:

- A 53 percent reduction in postoperative mortality, and a 64 percent reduction in morbidity.[44]
- Researchers at Stanford found that the observed/expected mortality rate declined from .88 in quarter one to .80 in quarter two.[45]
- An increase in reported very serious, largely preventable patient safety incidents that should not occur if the relevant preventative measures have been put in place (Patient Safety Never Events), with a

Figure 1. The WHO Surgical Safety Checklist


Surgical Safety Checklist

World Health Organization | Patient Safety

Before induction of anaesthesia → **Before skin incision** → **Before patient leaves operating room**

Before induction of anaesthesia
(with at least nurse and anaesthetist)

Has the patient confirmed his/her identity, site, procedure, and consent?
☐ Yes

Is the site marked?
☐ Yes
☐ Not applicable

Is the anaesthesia machine and medication check complete?
☐ Yes

Is the pulse oximeter on the patient and functioning?
☐ Yes

Does the patient have a:

Known allergy?
☐ No
☐ Yes

Difficult airway or aspiration risk?
☐ No
☐ Yes, and equipment/assistance available

Risk of >500ml blood loss (7ml/kg in children)?
☐ No
☐ Yes, and two IVs/central access and fluids planned

Before skin incision
(with nurse, anaesthetist and surgeon)

☐ **Confirm all team members have introduced themselves by name and role.**

☐ **Confirm the patient's name, procedure, and where the incision will be made.**

Has antibiotic prophylaxis been given within the last 60 minutes?
☐ Yes
☐ Not applicable

Anticipated Critical Events

To Surgeon:
☐ What are the critical or non-routine steps?
☐ How long will the case take?
☐ What is the anticipated blood loss?

To Anaesthetist:
☐ Are there any patient-specific concerns?

To Nursing Team:
☐ Has sterility (including indicator results) been confirmed?
☐ Are there equipment issues or any concerns?

Is essential imaging displayed?
☐ Yes
☐ Not applicable

Before patient leaves operating room
(with nurse, anaesthetist and surgeon)

Nurse Verbally Confirms:
☐ The name of the procedure
☐ Completion of instrument, sponge and needle counts
☐ Specimen labelling (read specimen labels aloud, including patient name)
☐ Whether there are any equipment problems to be addressed

To Surgeon, Anaesthetist and Nurse:
☐ What are the key concerns for recovery and management of this patient?

This checklist is not intended to be comprehensive. Additions and modifications to fit local practice are encouraged.

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corresponding decrease in the number of Patient Safety Never Events related to errors or complications from 35.2 percent to 24.3 percent. [46 47]

The WHO checklist was found to have a significant positive impact on improving health outcomes, decreasing surgical complications, and decreasing surgical site infections.[48]

Key Learning: Training in the use and design of checklists, support from management and administration, and the ability to format the checklist to best fit both the environment and the organizational culture are key factors in the successful implementation of checklists in any work group.

Key Points: The following were observations and learnings gleaned from various successful implementations of the WHO Surgical Safety Checklist developed by the World Health Organization that we can profit from.

Studies suggest that the checklist may reduce errors for the following reasons: it ensures that all critical tasks are carried out, it encourages a non-hierarchical team-based approach, it enhances communication, it catches near misses early enough to correct them, it anticipates potential complications with time for addressing them, and it encourages the use of technologies to manage anticipated and unanticipated complications.[49]

Practical issues encountered during the implementation, such as confusion about who should read each section of the checklist and when to do the checks, can be minimized by training. These issues may seem trivial but they can prove to be important when teams of professionals are attempting to use the checklist.[50]

The general conclusion of the process was that the checklist works because it is seen as more than just a tick sheet; adopting the checklist also means changing local systems and a commitment to teamwork for safety.[51]

IV. Nuclear Power

The world of nuclear power has a different operational and validation process than most other industries due to the high-risk nature of the work. Nuclear power plants have literally thousands of monitoring devices that groups of control room operators need to be aware of constantly. Any of these gauges, analog meters, panels, alarm tiles, CRT displays, and digital meters can display a number of different states at any given time. Monitoring activity is integrated with other responsibilities of managing day-to-day tasks for generating power.

For the control room operator, it's not just a matter of vigilance, attention, or visual perception. There are a number of other challenges that makes monitoring the equipment more of an active problem-solving task than simply one of vigilance. The challenge is not how to pick up subtle abnormal indicators in a quiet background. Rather, it is how to identify and pursue relevant findings against a very noisy and mentally chaotic background.[52]

Checklists are definitely part of the operation of the nuclear power plant as we will see, and there are several other practices that work in collaboration with checklists that we can learn from in building a safety culture.

Unlike airline pilots, who are in control of their aircraft, nuclear plant operators function in a supervisory control role, monitoring the status of the plant while it is being controlled by automation.[53]

Cause: Large-scale nuclear incidents, such as those at Three Mile Island and Chernobyl, are rare. This reality leads to the oft heard characterization of the work of nuclear plant operators and their process control tasks as 99 percent boredom and 1 percent sheer terror.[54] With thousands of components and instruments in the control room, equipment failures are bound to occur on a regular basis. There are always components, instruments, or subsystems that are missing, broken, working imperfectly, or being worked on. The vast majority of alarm messages on the alarm CRTs do not require operator action, and that may be as high as 50 percent. This puts a great burden on operators to distinguish those infrequent alarms requiring action and the more frequent ones that do not.

The operator's understanding of the status of the unit's components, and expertise in interpreting that status, provides the background or context for monitoring. Comprehensive monitoring in the nuclear power plant is not just a matter of reading the components but is dependent on the operator's mental model of the status to determine what is normal or abnormal given the current state of the unit.[55]

Operators have to cope with normal and abnormal operations on-line and in real-time. Failure to cope with abnormalities effectively can pose tremendous threats to the public and the environment. This great hazard potential puts a heavy burden on operators, while they live with a great deal of uncertainty about the true state of the plant because of incomplete and noisy information.[56]

Process: The process for ensuring safety in a nuclear power plant environment include checklists to be sure, but integrated checklists with many other processes and tools to help ensure a greater measure of safety. The following were all part of the steps taken in the control room to ensure that status of equipment was both noticed and communicated:

- Shift change updates
- Log entry availability
- Routine testing per shift
- Audio indicators and visual alarm screens
- Control panel monitoring
- Field operator checklist reviews
- Control operator field tours [57]

Experience and expertise are important when interpreting data in the control room. During the execution procedures, operators always try to understand the intent of the test and not merely follow the procedural checklist in a rote fashion. In doing so, they proactively monitor certain parameters to confirm that the test is going as planned.

During emergency conditions, operator performance is highly governed by a read-and-do checklist of procedures. These checklists provide detailed guidance on what parameters to check, how to interpret the data observed, and what control actions to take.[58] While following these checklists to the letter, operators were also monitoring the state of the plant and assessing the appropriateness of the procedures they were following at each point in time to ensure the tasks fit their understanding of the plant state. [59]

Results: The nature of the role control room operators play necessitates that they use their experience, as well as checklists, to determine what needs to be addressed and when. The results of these activities include the ability to:

- Catch and recover from errors—both operator errors and errors in the procedures due to the plant state.
- Assess whether the procedural checklist path they are following is correct, or whether they missed an important transition.
- Fill in gaps and adapt procedures to the situation.
- Deal with unanticipated situations that went beyond the available checklist procedural guidance.

Key Learning: Checklists are only as good as the people using them. They do not supplant the need for effective training, understanding only gained from experience, and other processes, methods, and tools that together form an arsenal of effective approaches to mitigate risk.

Key Points: The following are takeaways from the domain of nuclear power plant operators and their need for flexibility, experience, skill, and mental models to assist in determining responses to alarms and unanticipated situations, and how checklists are to be implemented:

- Monitoring of alarms and various plant state indicators plays a heavy role in the operation of the nuclear power plant.
- A mental representation of the situation plays a central role in making decisions as to what steps, if any, the operator needs to take or checklists used.
- Decision-making by operators is based on the mental representation of the factors known or hypothesized in their ever changing influence on the plant state at any given point in time.
- Pre-planned procedures and checklists are useful, but have limitations due to the confluence of influencing factors on plant state and alarms, and necessitate the need for operators to develop diagnostic and response strategies on their own in real time based on experience, collaboration, and attentiveness.[60]

V. MINING

The world of mining is a world of work several hundred meters underground, where it's dark, hot, wet, and in many cases performed on steep terrain. It is a world of hard labor and dangerous conditions where many believe, not unlike that of medical personnel, that deaths are inevitable in large mining operations. [61] If this singular analysis is any indication, it is an industry where safety often takes a back seat to production and profits.

The analysis of this situation revealed that a total safety program and culture change, part of which was the use of checklists, was the approach required to address all issues of the hazardous environment. The lessons learned can be insightful.

Cause: The mining industry is characterized by accidents and deaths. The following are some causal factors that necessitated a refocus on safety, and a commitment to make the environment one that was as safe as possible for those brave souls that labor under those conditions:

- A company had suffered 200 worker fatalities worldwide over the previous five years.
- Working conditions under which miners labored are extremely challenging.
- Various cultural groups have to work closely together with no common language.
- The literacy rate is low.
- Safety statistics for the mining industry as a whole was horrifying. [62] [63]

Process: The situation was of such a critical nature in one mine employing more than 30,000 workers that the following steps were taken to identify what direction to pursue:

- The total operation had to be shut down indefinitely.
- A top-to-bottom audit of safety processes and infrastructure was conducted.
- All safety procedures had to be overhauled with new guidelines and checklists developed.
- Small-group meetings and face-to-face communication between executives and individual employees were used to identify what went wrong in the past and to instill personal and group responsibility.
- The entire workforce was brought together in sports stadiums for leadership engagements to demonstrate the commitment to change.
- Lower-level managers, union leaders, and government representatives were included in redefining the standards for the safety program to ensure those implementing the program had buy-in.[64]

One safeguard implemented to promote better health was good engineering practices to reduce noise, dust and vibration, thereby preventing exposure at the source.[65]

A safety checklist was developed for pre-operation vehicle inspections to meet minimum performance requirements for managing those areas where high-risk has resulted in the majority of fatalities in recent years.[66]

A procedure and checklist system was implemented for pre-operation inspection to ensure safe operation of all surface mobile equipment. When the equipment fell outside the parameters of the defined group, a risk-based approach was used to determine the level of compliance needed for each specific requirement.[67]

Results: The goal to address the safety issues was tackled head on and commitment to a zero-harm culture was the challenge. Some long-term management employees indicated they did not think the goal was realistically achievable. Thus, many employees were not prepared to change, and almost all managers at that mine were replaced.

Fatality reduction resulting from the enhanced safety program fell dramatically from 44 in 2005 to 17 in 2011 and 13 in 2012.[68] Time lost due to injuries was cut by more than 50 percent.

During 2013, the lost time injury frequency rate was reduced by 18 percent.[70]

Key Learning: The effective use of checklists necessitates a culture change that focuses on safety where checklists are viewed as more than simply tools, but where there is confidence in them and a shared vision that they will contribute to improving safety, raising quality, and increasing productivity when used in conjunction with other processes, methods, and tools.

Key Points: The lessons learned from the mining industry, although dramatically different in context, are not substantially different from other industries and provide principles in the implementation of checklists, including:

- Safety was a leading indicator of wider performance—if you got safety right, then other things would follow; from stronger relationships with unions and governments, to productivity, and efficiency across the board.[72]
- A zero-mindset was necessary, and a belief that all injuries and occupational illnesses were preventable.
- Simple, non-negotiable standards, guidelines and checklists had to be consistently applied across all operations.
- “No repetition of incidents” was a guiding principle, and if an incident occurred it was necessary to learn from it to prevent the same incident from happening in the future.[73]

VI. RAIL TRANSPORTATION

The rail transportation industry is mired in an organizational culture that is not far removed from what it was when it began operations in the early years of the industrial revolution. The only other large organization existing at the time was the military, and the rail industry modeled its structure on the military. The inherent inadequacies of that structure have plagued them and have had a detrimental impact on their safety record.

Cause: As in the airline industry, it took a tragic seminal event detailed by the National Transportation Safety Board (NTSB, 2006) to spur the need for a pilot safety process at Union Pacific Railroad.

In the early morning of June 28, 2004, the 74-car Union Pacific train rolling at 44 mph passed a red signal just east of the small community of Macdona, Texas. Immediately ahead, the 123 cars of a BNSF Railway train were pulling off the main line onto a siding. The Union Pacific train, its throttle remaining open at the Number 3 notch, struck the midpoint of the BNSF train.

The impact derailed all four 200-ton Union Pacific locomotives. Nineteen additional Union Pacific cars piled up against the locomotives, some of them breaking open and spilling their contents. Among them was a tank car that sustained an 11-inch rip from which escaped over 50 tons of liquid chlorine that instantly vaporized, forming a cloud of poisonous gas—1,400 feet across—that engulfed the UP locomotives and two homes near the tracks.

Lying under the debris, but not seriously hurt, the crew members of the Union Pacific train smelled the chlorine inundating their cab and extricated themselves from the wrecked locomotive to escape the gas. As they attempted to walk toward clean air, the conductor’s breathing became increasingly labored and he could not continue. The engineer, himself suffering from respiratory distress, found that he could not carry him. The conductor’s body was found a few hours later by firefighters. Two people in one of the homes nearby were also found dead. At least 30 others were injured.

After declining between 1976 and 1986, accidents, injuries, and fatalities have held at a steady rate for nearly 25 years, indicating the current system has reached its limit and further advances in safety require new approaches.

A series of fatal accidents led workers and management to question traditional approaches to safety.

Many new employees were inducted into the ranks of workers requiring safety orientation.[75]

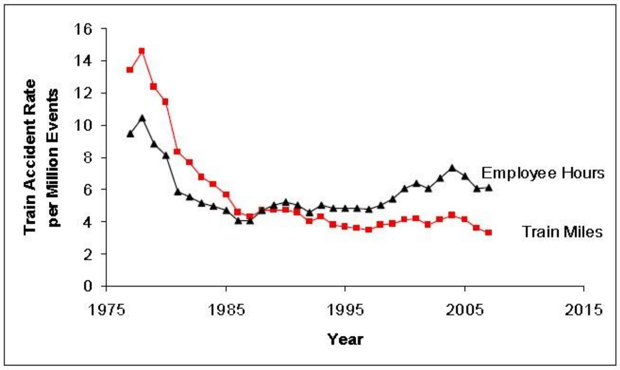

Figure 2. Train Accident Rate by Train Miles and Employee Hours (From FRA (2008)) 74

Process: The need to address safety was obvious, and a program was developed to improve safety by removing barriers or limits associated with safety throughout the organization. Included in the process were the following:

- The focus to bring about change was to evaluate potential risk and unsafe conditions and practices that might lead to events rather than examining catastrophic events themselves.

- A pilot program called Changing At-risk Behavior (CAB) was implemented.
- The CAB began with regular peer-to-peer feedback sessions. These were conducted by trusted colleagues after they had made observations during a ride-along to provide input on observed behaviors to improve alertness and teamwork among locomotive cab personnel on the road.[76]
- To improve crew attention, and situational awareness, procedures were implemented that included cross-checking between the engineer and the conductor, confirming their perceptions of the hazardous conditions, not unlike the cross-checks performed in the cockpit between members of an airline flight crew.
- A checklist was also developed to record data from feedback provided train crews, and included behaviors related to more restrictive information than what may be called for under hazardous procedures and alertness to these high-hazard conditions.
- A separate checklist and training curriculum was created for switching activities that included behaviors associated with safety in the yard, and with safety under general industrial conditions. Workers were trained and coached to conduct feedback sessions. [77]

Results: The results of the pilot test at Union Pacific was promising and should provide a basis for expansion to other organizations in the railway transportation industry, and similar organizations in other industries.

Process metrics indicated that the commission of at-risk behaviors decreased by approximately 80 percent. Systemic safety conditions improved when management and workers removed barriers to safety, and the rate of engineer decertification due to repeated safety violations gradually declined by 79 percent after the program introduction, while decertification rates at comparison sites did not decline. The rate of derailments and other incidents also decreased by 81 percent at a yard with a strong CAB program implementation.

Labor and management relations improved with greater trust and cooperation, general safety awareness, personal responsibility for safety, and safety dialog improved. A 17 percent increase in the prevalence of safe behavior was cited, as well as a 57 percent reduction in injury frequency.[78]

Key Learning: The development of checklists is not a management dictate, but a grassroots program where managers, engineers, technicians, operators, and every other job role is involved in the production and implementation of checklists.

Key Points: The following were observations or actual feedback provided by participants in the pilot study at Union Pacific that give us guidance in the implementation of checklists:

- Most of the respondents said training classes and feedback positively changed personal behavior. Classes were seen as "more of a good thing" and were valuable to helping to keep safety on the minds of workers.
- Worker buy-in seemed to be influenced by the fact that this was not a management program. Having another engineer or conductor out there looking over their shoulder gave the program more capital.
- Committed samplers (those who observed and provided feedback) who "owned" the process and had relationships with those they sampled were more effective.
- Internalization and generalization was central to the process of change in the program. Most participants mentioned a change in communication as an outcome of the CAB program. People were talking about safety differently compared to how they communicated before CAB was implemented.
- Placing a peer "safety expert" in the locomotive cab or in the yards stimulated discussion on safety. This led crews to accept talking about safety as a smart thing to do. The dialog was a catalyst for paying attention to risks and being more alert overall both in and out of the cab.
- Workers expressed feeling empowered over their own safety. They reportedly felt more comfortable with their safety-related choices and were more likely to confront a manager who required them to perform an unsafe procedure when a safer way was more feasible.[79]

VII. CONCLUSION

The following implications, drawn from this analysis of processes undertaken to build a safety culture and in the use of checklists in numerous industries, provides insightful principles and practical strategies on how the development of critical checklists can have a positive impact on the development of a safety culture:

Understanding checklist use:

The use of checklists will not eliminate all accidents in the lab, test facility, production line or wherever they are implemented. Accidents will still happen even when users make decisions consistent with best practices because risk cannot be completely eliminated.

Training classes and feedback can positively change personal behavior. Classes are valuable in helping to keep safety on the minds of workers. Practical issues encountered during the implementation of checklists can be minimized by effective training.

All employees must make decisions as to what steps, if any, they need to take based on a mental representation of the factors known or hypothesized in the ever-changing or semi-constant state of their equipment at any given point in time.

"No repetition of incidents" must be a guiding principle, and if an incident occurs it is necessary to learn from it to prevent the same incident from happening in the future.

Internalization and generalization is central to the process of change. Communication should not be undersold. A change in communication can get people talking about safety differently than they communicated before an effective safety awareness program was implemented.

Emphasis must be placed on the importance of checklist use with reminders of situations where deviations from checklists occur and how they can be misused.

Organizational changes that support checklist use:

It is crucial that performance evaluation and theoretical rhetoric proclaim the same message. When employees are measured on one thing, while the rhetoric emphasizes the importance of checklists and safety, they know where the organization's priorities fall and how they need to perform.

Engaged senior leadership is essential to sustaining a culture of safety and the involvement of all levels of staff is critical to a successful safety and checklist initiative roll-out. Staff buy-in goes hand-in-hand with staff ownership—if staff members participate in the development and execution of the initiative they are more apt to follow the guidelines and produce positive results.

Safety and checklists must be ingrained in organizational culture until everyone can say that checklists are just a part of how we do business.

One key to organizational success in the use of checklists is to continue to search for errors, know their error rates, monitor them after implementing safety innovations, and give feedback to all staff so they know the science behind the checklists is valid. *The use of checklists is not the end-game; reduced error rates are.*

A key feature of a successful safety and checklist initiative is its rejection of a command-and-control regime where workers are simply told they are to use a checklist and expected to go and do it. Instead, they need to be encouraged to develop checklists that fit their own unique challenges and culture. Worker buy-in is greatly influenced by safety programs that are not management driven.

To improve safety, it is critical that we shift from a perception where the prime cause of accidents is user errors to thinking of errors as the consequence of many factors that combine to create conditions for accidents, and how to reduce those conditions.

A zero mindset to injuries, accidents, and occupational illnesses is necessary, and a belief that all injuries and occupational illnesses are preventable.

Committed peer champions placed as "safety expert" in labs, test facilities, or manufacturing plants will stimulate discussions on safety. This will lead to discussions about safety as a smart thing to do and will become a catalyst for paying attention to risks and being more safety alert.

Benefits of checklists:

A checklist is a tool that can reduce errors by ensuring that all critical tasks are carried out, encouraging a non-hierarchical team-based approach, enhancing communication, catching near misses or potential complications early enough to correct them, and encouraging the use of technologies to manage anticipated and unanticipated complications.

Checklists are a good way of making certain that tasks get done, but determining the best way of proceeding in a complex operational setting is to acknowledge expertise and experience as an essential foundation to the use of checklists.

Pre-planned procedures and checklists cannot replace the necessity of users bringing to bear diagnostic and response strategies in real-time based on their experience, collaboration, and attentiveness when the confluence of influencing factors on any given piece of equipment, test, or facility requires it.

Workers will feel more empowered to control their own safety, more comfortable with their safety-related choices, and are more likely to confront anyone asking them to perform an unsafe procedure when a safer one is available.

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