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THE WORKER EXPOSURE FAILURE MODES AND EFFECTS ANALYSIS

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The Worker Exposure Failure Modes and Effects Analysis (WE-FMEA) is a new approach to quantitatively evaluate worker risks from possible failures of co-located equipment in the complex environment of a magnetic or inertial fusion experiment. For next-step experiments such as the International Thermonuclear Experimental Reactor (ITER) or the National Ignition Facility (NIF), the systems and equipment will be larger, handle more throughput or power, and will, in general, be more robust than past experiments. These systems and equipment are necessary to operate the machine, but the rooms are congested with equipment, piping, and cables, which poses a new level of hazard for workers who will perform hands-on maintenance. The WE-FMEA systematically analyzes the nearby equipment and the work environment for equipment failure or inherent hazards, and then develops exposure scenarios. Once identified, the exposure scenarios are evaluated for the worker hazards and quantitative worker risk is calculated. Then risk scenarios are quantitatively compared to existing statistical data on worker injuries; high-risk scenarios can be identified and addressed in more detail to determine the proper means to reduce, mitigate, or protect against the hazard. The WE-FMEA approach is described and a cooling system maintenance example is given.

I. INTRODUCTION

Safety assessment techniques currently used by industrial safety professionals tend to be qualitative; they are used mainly to identify hazards and the personal protective equipment needed for deterministic protection against the hazards. This approach is typified by the 29CFR1910.134 technique that directs a walk-through of the workplace to identify task hazards. The foremost tool used for the qualitative approach is the Job Hazard Analysis (JHA) that deconstructs a task into its major parts or actions to identify the hazards of energy or hazardous material exposure.[1,2] The JHA is quite useful in developing safety procedures for tasks and recommending personal protective equipment for workers to use during performance of tasks. For the state-of-the-art JHA, the industrial safety professional judges the degree of hazard subjectively and protective measures are adopted based on the safety professional's intuition, guidance from best industry practice, regulation, or some combination of all of these. The JHA can also identify the hazard for follow-up detailed analysis.

The JHA is a proven analysis tool that has worked well for many situations that require workplace safety assessment.[3] The JHA has been used for decades; however, the JHA focuses on the task the worker is performing. In a simple working environment, such as a large shop with few indirect or proximate hazards apart from the task at hand, the JHA performs well and gives a complete analysis of hazards. For example, in a manufacturing plant with defined work areas, workers have the primary concerns of overexertion, falls, tool handling injuries, hand wounds, cuts and pinches from moving parts, and impacts from work pieces;[4] there are few secondary hazards of concern. In a complex working environment, such as a fusion experiment, a particle accelerator, or a power plant, there can be a number of other hazards peripheral to the task at hand. In such an environment, the workers access areas that pose multiple hazards from systems and equipment that are in close proximity to the workers, but are not part of the work to be performed. These nearby systems or equipment may or may not be de-energized. Such indirect or proximate hazards are not typically included in the JHA. The JHA may address general issues about the work environment, such as high room air temperature or radiation exposure, but this is not sufficient to provide comprehensive worker protection in a complex fusion facility.

Other worker safety assessment methods have been developed in the past decade, primarily to evaluate worker risks during environmental cleanup tasks.[5-8] The worker safety methods developed in the 1990's for environmental cleanup focus on the consequence assessment aspects of worker exposure to the process hazards, namely radioactive, toxicological, and mixed wastes that are handled and packaged in remediation work. The safety concerns in cleanup work arise from the task at hand, such as dealing with flammable gases in waste drums, potential fission criticality of the waste materials, and hazardous material exposure during handling. Once again, the focus is on the primary hazards facing the workers. Perhaps the most definitive publication on worker safety methods is Harms-Ringdahl;[9] it also focuses on the primary hazards of the task at hand. The new worker safety approach described here augments these past approaches since its focus is on peripheral or secondary hazards nearby rather than the primary hazards of the energy sources and hazardous materials in the task at hand. While these primary hazards usually have the greatest influence on worker safety, if the workers are properly following their procedures and using personal protective equipment – as we expect in a first of a kind fusion facility – then secondary hazards that have not been analyzed or guarded against can have the greatest influence on their safety.

II. WORKER EXPOSURE FMEA METHOD

To address the hazards of proximate systems and equipment, a modification to the system-level Failure Modes and Effects Analysis (FMEA)[10] is proposed. The FMEA is already a proven, respected technique in the many industries.[11-14] Fusion designs have also made good use of the FMEA.[15] The analysis tool is known for its systematic evaluation and ranking of faults that can occur in the system under study. The traditional FMEA is applied to all the major components of a given system to be evaluated, even when the system components are in multiple rooms or floors of a facility. To address worker safety, the system-level FMEA has been modified to identify all of the components posing potential hazards to the worker. For this application, the system-level FMEA approach is used not with a system component boundary; instead the Worker Exposure FMEA (WE-FMEA) analyzes only the components that are near the worker's location (i.e., within the same room or perhaps within ~10 m of the worker). The set of components close to the worker will almost always reside in a number of different systems; the set also includes those distant components whose failure can directly affect the worker's location, such as ventilation fans. Therefore, WE-FMEA treats the proximate components from a number of systems, instead of the components from one entire system. The WE-FMEA further alters the traditional system FMEA to only consider equipment failure modes that can present an immediate hazard to the worker rather than all known equipment failure modes. Also, the WE-FMEA failure effects are the injury consequences to the worker rather than component failure effects to its parent system. The WE-FMEA uses the systematic nature of FMEA to identify hazardous events arising from component failures and records a preliminary quantification of the probability of the component failures. With the type of industrial injury and the probability of component failure identified, the risk to the worker can be calculated.

Personnel injuries can vary a great deal in the actual damage inflicted. Classifying injuries can be performed based on the part of the body affected, the severity of the injury, the ability to heal or recover from the injury, physical impairments that may result from the injury, or other factors. Due to this variety of classifications, typifying injuries for assessing the human injury consequences of a component failure is problematic. For this paper, the 'Abbreviated Injury Scale' from emergency medicine[16] has been used as a starting point to categorize injury severity. Potential injuries are qualitatively ranked as one of six levels, defined here as:

1. Minor Injury (MI): first aid cases or injuries that do not result in lost work days, the worker is released to return to the job after receiving aid (i.e., contusions, abrasions, lacerations, mild sprains, etc.);
2. Moderate Injury (MoI): cases where the worker leaves the job to obtain medical treatment but does not require emergency medical help (large or deep lacerations, muscle strain, sprains, small burn areas, etc.). A MoI may result in lost work time;
3. Serious Injury (SI): worker injuries that require emergency medical help and result in one or more lost work days (individual bone fractures, mild concussion such as from a standing fall to the floor, modest area burns, very large lacerations, penetrating wound with mild organ damage, some blood loss, etc.);
4. Severe Injury (SeI): worker injuries that require immediate emergency medical help and result in perhaps a week or longer of lost work days (moderate area burns, many broken bones from a fall from modest height, concussion, mild eye damage, moderate organ damage, large blood loss, etc.);
5. Critical Injury (CI): worker injuries that require immediate emergency medical help, results in weeks of lost work days, and may not ever return to that type of work again (such as deep or large area burns, electric shock, severe organ damage, memory loss from asphyxiation, eye loss, injuries from a fall from height, very large blood loss, etc.);
6. Unsurvivable or Fatal Injury (FI): the sustained injuries result in immediate fatality or are the direct cause of delayed fatality (such as organ damage to the point of organ failure, brain trauma, extreme blood loss, high percentage body burns, electrocution, fatal fall, etc.).

The WE-FMEA analysis steps are to first identify the maintenance or other plant activity to be analyzed and the work location within in the facility. Next, the literature should be surveyed to determine the types of hazards and injuries that have occurred when performing the same task or similar tasks in similar facilities; in this case, other fusion experiments, particle accelerators, or other facilities with a system similar to the one under consideration. Next, the personnel safety master logic diagram[17] or other methods, such as checklists, can be used to identify the types of energy sources and hazards in the vicinity of the worker's activity (maintenance, calibration, etc.). With this information, the pieces of equipment and their failure modes that could create local hazards in a ~10 m-diameter sphere around the worker are systematically identified. Next, any remote equipment necessary for worker protection that has not been addressed already in the JHA must be identified. Example equipment could include ventilating fans, ventilation dampers, chillers, area monitors, circuit breakers, lights, etc. These equipment items are recorded on a worksheet similar to a traditional FMEA worksheet. The worksheet entries are evaluated for these 'secondary risks' to the workers. If the secondary risks are low, no additional safety provisions are required. If the secondary risks are high, then the analyst must assess if any of the personal protective equipment (PPE) issued for primary hazard protection will offer some protection for the secondary hazard. If the PPE also protects the worker from secondary hazards, then the task is complete. If not, then the analyst must identify the additional means that are needed to mitigate or reduce the secondary risks by using engineering or administrative controls on the task. The WE-FMEA must be used in concert with a JHA or other worker task based assessment to determine the protective measures (buddy system, camera surveillance, radio, etc.) and protective equipment the worker will be using for protection from primary and secondary hazards.

III. WE-FMEA EXAMPLE

As an example of this method, the WE-FMEA is applied to a representative task of a yearly, 4-hour calibration of a cooling water instrument in the first wall (FW) cooling system of a magnetic fusion experiment. The cooling systems for the experiment use water, similar to the ITER design. The instrument maintenance task would be performed in a cooling system room that contains the main cooling equipment and piping for divertor and FW cooling. Fig. 1 shows a suggested room layout for the example task. Since fusion designers are aware that placing instrumentation in a high magnetic field can lead to inaccurate readings, there is an expectation that the magnetic field strength will not be high in the work area. Both cooling systems have piping, pumps, valves and heat exchangers near the worker's location. There is a residual radiation field from the activation in the coolant water. The coolant system equipment room also operates at a somewhat elevated temperature and with high noise due to the large pump motors, assumed to be in the 4 to 13 kV size range. There may or may not be plasma heating conduits routed through the room, which presents the possibility that leakage electromagnetic radiation from the conduits could be present in the room. Design details of the room are not complete for this example; some assumptions have been made. The FW cooling system itself is assumed to have been "safed", that is, cooled down to room temperature and depressurized. This is a safety precaution for the personnel and it also serves as a calibration point in the instrument calibration process (i.e., "zeroing" the instrument). The adjacent cooling systems are assumed to be active since there must be active cooling for decay heat removal from the tokamak. Typical plasma operation could require the divertor cooling system to operate at 150 C at 4 MPa; however, the cooling system might be operating at a reduced value when only removing decay heat. Even at reduced heat transfer conditions, the system will be pressurized to suppress coolant boiling. Perhaps the coolant parameters in decay heat removal mode will not create steam during a pipe breach event, but spraying 60 C liquid water still constitutes serious burn and ocular hazards.

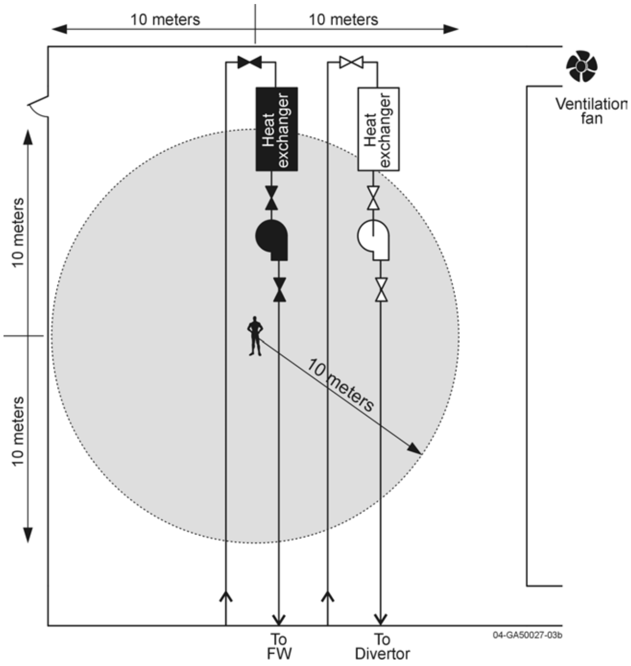

Fig. 1. Illustrative room layout for the WE-FEMA example.

Following the WE-FMEA steps outlined above, the US Department of Energy (DOE) Occurrence Reporting and Processing System database was searched for events related to pressure instruments. The results were several events of not securing power to the instrument before starting work, leaks and spills associated with the instrument work, safety issues of working at height, and some burns sustained from nearby piping. The first three concerns - securing power, handling coolant leaks/spills, and working at height – are expected to be addressed in the JHA. The fourth concern, burn injuries from nearby piping, is exactly the type of issue that the WE-FMEA can identify and a JHA may or may not identify because the primary work is on an instrument and pipe at room temperature. Calibrating the pressure instrument can also mean exposure to radiation in the coolant from activated corrosion products, and the potential for skin contamination if the FW coolant leaks. The JHA would probably specify anti-contamination clothing – gloves, tyvek coveralls, booties, possibly a hood, and some type of face shield to protect against splashing. The workers would probably not require breathing apparatus since the task is conducted at room temperature and pressure and is not expected to generate any gaseous or particulate emissions. If the workers are on a tall scaffold to access the pressure instrument, they will also have fall protection equipment specified.

The WE-FMEA example for FW cooling system instrument calibration is given in Table I. Several possible energy and hazardous material releases were identified when considering a generic equipment room. The piping in adjacent systems was evaluated based on an assumption that the worker is > 1 m outward from a break location. As a first approximation, the injury consequences are considered to decrease as the workers' distance from the breach increases; the 1 m is a distance that should protect against pressure jet effects. The WE-FMEA shows that steam or hot water leaks could occur, albeit at a low probability over the time frame of the task. The expected anti-contamination clothing for this instrument calibration task is deemed inadequate to protect against high temperature and pressure water release, or steam release, in the area.

The American Petroleum Institute (API) has provided some worker safety guidance on steam releases and exposure.[18] When modest pressure steam is released, the steam jet fans out and slows within about a meter from the break, and the steam cools to 100 C just after exiting the breach. The steam also heats up the room air. At a concentration of 20% steam in the air, the steam/air mixture cools to about 60 C. Using 60 C as the minimum temperature for human burn injury from steam/air exposure, the API determined the steam-affected areas around a breach location and developed simple relations to estimate these areas. For continuous steam leaks the affected floor area is calculated by the formula $A = 0.6(x)$, where x is the steam release rate in pounds/second, and A is floor area covered by 20% or more steam, in square feet. Presumably, the affected height is the floor-to-ceiling height. For our modeling purposes the floor area was assumed to be rectangular and centered around the break location. Considering water systems, the generally accepted leak rate is up to 50 gallons/minute, and pipe ruptures are greater than that value.[19] As a first approximation, converting a 50 gallons/minute water leak into a steam leak is ~3 kg/s. Using the API formula with this leakage gives 0.37 m^2, or an affected floor area of 0.6 m by 0.6 m. For the worker > 1 m distant from the pipe, there is no immediate threat, or no injury (NI). For a pipe rupture, what the API calls an instantaneous steam release, the affected area equation is $A = (63.317)(x^{0.6384})$, where A is the area in square feet and x is the release mass in pounds. A rupture release could begin at ~3 kg but will typically be much larger, such as 455 kg. For the 455 kg case, the affected area is about 22 by 22 meters. For this example, the 22x22 m floor area will be the assumed value for pipe ruptures and shell breaches, such as pump bodies and valve bodies. The heat exchanger shell breach is assumed to allow a larger release and will therefore pose a higher hazard. The worker is assumed to be less than 10 m from adjacent system pumps, valves, and heat exchangers in the example.

Exposure to steam will result in thermal burns and steam inhalation injury, as well as activation product exposure. The severity of steam injury is related to the temperature of the steam, the duration of exposure, the distance of the worker from the source of the steam, and the ability of the worker to escape the steam.[20] Burns are judged based on the percent of body surface area (BSA) affected, and the age of the injured person.[20] For example, the 45 to 64 year-old age group results are: 10% BSA has a ~1% mortality, 20% BSA has a 5% mortality, 30% BSA has a 15% mortality, 40% BSA has a 20% mortality, 50% BSA has a 60% mortality, 60% BSA has an 80% mortality, 70% BSA has a 90% morality and higher BSAs have 100% mortality. The "rule of nines" is used by medical personnel to estimate BSA. An adult's arm is 9% of their BSA, the front and the back of the trunk of the body are each 18%, and each leg is 18%. The face is 9%, and the crotch is 1%. For an initial estimation, the closer a worker is to a steam leak, the greater the steam engulfment and the higher the BSA affected. As a first approximation, 70% BSA and higher is assigned the FI level, 50-60% BSA is CI, 30-40% BSA is SeI, 10-20% BSA is SI. Under 10% BSA, not only does the human body have high capacity to survive a burn, but medical science has advanced to aid the burn patient; no mortality is given. Inhaling steam usually creates pulmonary injuries that exacerbate the skin burn injuries. The medical viewpoint is that steam has more damage potential than hot, dry air. The additional heat deposition from inhaled steam leads to hypoxia, anoxia, edema, and shock.[20] Hence, the medical community views steam as more dangerous than smoke or hot air; with the advances in burn care some medical personnel believe that inhalation injury to the lungs is the main cause of mortality in burn patients.[21,22] The steam can damage lung tissues and lead to pulmonary congestion, edema and pneumonia in the lungs, complicating recovery from skin burn injuries. If the worker or workers are on a scaffold to work at height, evading a steam release is not possible in a timely manner. This was tragically shown to be the case when a steam pipe failed at the Oconee nuclear power plant in 1982.[23]

TABLE I. Example WE-FMEA for FW cooling water instrument calibration.

Proximate Component and System	**Potential Component Failure Mode**	**Potential Causes of Component Failure**	**Potential Hazards to Workers**	**Frequency of Component Failure**	**Worker Risk**	**Comments / Recommended Preventive Actions**
Coolant piping For Divertor	Piping leak	Erosion-corrosion corrosion, fatigue, weld flaw	Steam inhalation, jet exposure, rad. exposure	2.5E-10/h-m, 4 hour task, 1.2 m x 2 lines.	2.4E-09 NI	> 1 m distant worker is not at risk from 0.6 x 0.6 m leak.
Coolant piping For Divertor	Piping rupture	Embrittlement, weld failure	Steam immersion, inhalation, rad. exposure	2.5E-11/h-m, 4 hour task, 22 m x 2 lines.	4.4E-09 CI	< 10 m distant worker is at risk. 'Leak before break' may warn worker.
Coolant pump For Divertor	Pump casing leak	Erosion-corrosion, corrosion, fatigue, overstress	Steam inhalation, jet exposure, rad. exposure	3.6E-05/h 4 hour task.	1.44E-04 NI	> 1 m distant worker is not at risk from 0.6 x 0.6 m leak.
Coolant pump for Divertor	Pump seal failure, loss of coolant accident	Seal water flow failure, vibration, wear	Steam inhalation, rad. exposure	7E-08/pump-h, 4 hour task. Assume 22 m x 22 m affected.	2.8E-07 SeI	< 10 m distant worker is at risk. 'Leak before break' may warn worker.
Coolant pump for Divertor	Pump flywheel thrown	Shaft fatigue, bearing seizure, flywheel fatigue	Exposure to shrapnel	< 1E-06/year or 1E-10/h, 4 hour task.	4E-10 MoI	Assumed failure rate, assumed injury severity
Coolant pump For Divertor	Pump impeller thrown	Shaft fatigue, bearing seizure, impeller fatigue, impeller unbalance	Exposure to shrapnel, steam immersion, inhalation, rad. exposure	< 1E-06/year or 1E-10/h, 4 hour task; assume 22 m x 22 m affected.	4E-10 SI	< 10 m distant worker is at risk
Coolant pump for Divertor	Pump motor fire	Insulation breakdown, foreign material intrusion	Exposure to smoke, hot combustion products	1.8E-07/h, 4 hour task. Assume room fills w/smoke.	7.2E-07 MoI	Alarms for timely evacuation
Coolant pump for Divertor	Lubricant leak	Fatigue cracking, vibration	Exposure to hot lubricant, may also be mist of toxic material	1E-06/h, assumed value. 4 hour task.	4E-06 SI	Assumes use of nonflammable lubricant, 60 C, ~ 0.4 MPa. Mist is assumed to spread.
Coolant pump for Divertor	Noise of operation	Normal operation	Acoustic energy exposure	1, ambient environment	1 MI	Assume JHA specifies hearing protection
Coolant pump for Divertor	Exhaust heat from operation	Normal operation	Exposure to elevated room air temperature	1, ambient environment	1 MI	Assume exposures in task environments are limited [e.g., ref. 24]
Heat Exchanger for Divertor	Shell leak	Erosion-corrosion corrosion, fatigue, weld flaw	Hot water jet, possible radiation exposure	1E-08/h, 4 hour task.	4E-08 NI	> 1 m distant worker is not at risk from 0.6 x 06 m leak
Heat Exchanger for Divertor	Shell rupture	Erosion, embrittlement, weld failure	Hot water release, possible rad. exposure	1E-10/h, 4 hour task. Assume 22 m x 22 m affected.	4E-10 FI	< 10 m distant worker is fatally injured. 'Leak before break' may warn worker.
Coolant instrument for Divertor	Leak	Fatigue, weld flaw	Steam inhalation, jet, radiation exposure	1E-07/h, 4 hour task.	4E-07 NI	> 1 m distant worker is not at risk
Coolant instrument for Divertor	Ejection under pressure/rupture	Fatigue cracking, weld failure	Exposure to debris missile, steam inhalation, radiation exposure	~ 1E-04/year or 1E-08/hour, 4 hour task. Assume ~ 10% chance worker is struck.	4E-09 SeI	10% is an overestimate of primary impact plus ricochets.
Isolation valve for Divertor	Leak past the stem	Valve packing wear, foreign material intrusion on valve stem	Steam inhalation, jet exposure, radiation exposure	1E-06/h, 4 hour task.	4E-06 NI	> 1 m distant worker is not at risk from 0.6 x 06 m leak
Isolation valve for Divertor	Valve body rupture	Erosion-corrosion, corrosion, fatigue, casting flaw	Steam immersion, inhalation, rad. exposure	1E-10/h, 4 hour task. 22 m x 22 m.	4E-10 SeI	< 10 m distant worker is injured

TABLE I. Continued

Affective Component and System	Potential Component Failure Mode	Potential Causes of Component Failure	Potential Hazards to Workers	Frequency of Component Failure	Worker Risk	Comments / Recommended Preventive Actions
Ventilation fan for room ventilation system	fails to continue to run	motor fault, drive fault, blade imbalance	Exposure to elevated room air temperature	3E-05/h 4 hour task	1.2E-04 MI	May have redundant ventilation system, limits to work environment temperature [ref 24]
Ventilation damper for room ventilation system	fails closed	linkage fault, solenoid failure	Exposure to elevated room air temperature	3E-07/h 4 hour task	1.2E-06 MI	May have redundant ventilation system, limits to work environment temperature [ref 24]
Worker Risk Summations	No Injury, NI = 1.5E-04 MI = 1.0 Accident/Injury risk, MoI+Si+SeI+CI = 5E-06 over 4 h Fatality risk, FI = 4E-10 over 4 h					

Note: Failure rate values were taken from references 25-28.

Some of the failures in Table I could result in debris being expelled from rotating equipment, or ejection of objects under pressure. In enclosed concrete rooms that are traversed by piping, it is possible to ricochet debris from piping, structural columns, cable trays or the walls/floor. Thus, the probability of impact should be increased over the initial 'line-of-flight' impact probability that was coarsely estimated using a 2π geometry at 10 m radius and then ratioing an assumed human profile area to the hemisphere area. There are very sophisticated means available to determine the probability of impact from such debris, and one such method has been used for the National Ignition Facility in the case of a large capacitor failure that emits debris.[29] The level of detail of the example in this paper did not warrant analysis using a ricochet tracking computer code.

The results given in Table I are on a per worker basis, although the task may specify two workers to meet the 'buddy system' best practice in radiological work. From Fig. 1 and an initial review, the reader may believe that the risks are low and that passive components like pipes and heat exchangers do not pose hazards. Fission power plant experiences do not support this conclusion; there have been incidents that have caused extreme consequences and "near misses", meaning that no one was injured simply because they were not nearby when a failure occurred.[30-32] Overall, the risk values in Table I require interpretation since most of the individual events are low probability. The DOE Fusion Safety Standard[33] has stated that workers shall be protected from routine industrial hazards to a level commensurate with that of comparable industrial facilities, and that fusion facilities shall comply with US Occupational Safety and Health Administration regulations to control industrial hazards.

Occupational safety data from a comparable industrial activity, in this case fission power, can be used as a comparison point to the WE-FMEA findings. The US fission power industry has had a recent publication of occupational safety data,[34] that were compiled by the US Institute of Nuclear Power Operations (INPO). Yearly aggregate values for lost work time injuries, injuries resulting in restricted work, and fatalities (combined under the term "accidents") for nuclear power plants have been given in Table II. However, the accident data are not divided into the same level of resolution as the predictions in Table I. As a first effort to allow a comparison, using past ratios of fatalities to injuries of 0.6% in the 1980's,[35] and assuming a decrease to 0.45% in the 1990's and ~0.3% from INPO data in the 2000's produces some results. As an initial point of comparison, the accident/injury (MoI + SI + SeI + CI) values are compared to the Table II worker accident risk value, and FI values are compared to the worker fatality risk value.

From Table I, this example task of one instrument calibration for one system gave a fatality probability of 4E-10 over 4 hours, or a rate of 1E-10 fatality/hour. From Table II, the overall five-year average for nuclear power plant workers performing all plant tasks is 5E-09 fatality per hour, thus the example task is ~2% of the annual risk. The worker accident probability sum from the example task is 5E-06 over 4 hours, or 1.25E-06/hour; it is compared to the overall 5-year average for nuclear power plant worker accident/injury value of 1.4E-06/hour. Thus the accident/injury risk from the example problem is about 89% of the five-year average worker accident rate. The example task results pose a quandary; quantification shows that the fatality risk of this one example task is reasonably low but that a single 4-hour task comprises almost all of the annual worker accident risk. It is possible that the injury severities have been overestimated or that some of the failure rates are conservatively large values; both would result in overestimating the risk. If further investigation revealed that the failure rates and injury severity assessment are reasonable, then other means to reduce worker risk should be employed.

TABLE II. Worker risk in the US fission industry

Calendar Year	Accidents per worker hour	Fatalities per worker hour
1980	1.05E-05	6.30E-08
1984	7.50E-06	4.50E-08
1988	6.70E-06	4.02E-08
1990	5.15E-06	2.32E-08
1992	3.85E-06	1.73E-08
1994	3.20E-06	1.44E-08
1996	2.30E-06	1.04E-08
1998	1.45E-06	6.53E-09
1999	1.70E-06	7.65E-09
2000	1.30E-06	3.90E-09
2001	1.20E-06	3.60E-09
2002	1.10E-06	3.30E-09
5-yr average	~1.4E-06	~5E-09

This table assumes a 2,000 hour work year.
Data for 2001 and 2002 were taken from the INPO internet site.

Possible approaches are smart sensors that require less frequent calibration,[36] such as every two years instead of each year, or a digital sensor that can be remotely calibrated. These solutions either reduce or avoid the worker 'at risk' time in the room. A risk-benefit analysis could address the increased sensor cost versus using the traditional sensor with yearly calibration.

IV. WE-FMEA LIMITATIONS

Like every analysis method, the WE-FMEA has some limitations. The first limitation is that there can be some types of failure events that may be identified when examining the nearby components, but the failure events will not have failure rate data readily available. Some events will probably be very rare; they will not have any statistical data accumulated. In those cases, the WE-FMEA can be used qualitatively to support hazard identification, or an effort can be made to estimate or bound the required failure rate. Other events may have failure rate data, but as seen in the example, the failure rates may be conservatively high – this may be acceptable in a system failure fault tree, but not so easily accepted in a personnel safety assessment. Another limitation is that assessing personnel injuries is very subjective, depending on the physics of a component failure event and the physics of energy interaction with a human being. There are a few published guidelines regarding human tolerances and injury thresholds, notably aerospace data, and the Federal Motor Vehicle Safety Standards for automobile passengers, found in 49CFR571. Such data require collection, assessment and development for application to the consequence assessment in the WE-FMEA. While these institutions and the military have studied various aspects of human tolerances and injuries, injury prediction is not an exact science; for example, a test stand may have found that the force required to fracture a human bone is 1.1 kN, but if a smaller force from an impact is loaded at a detrimental orientation or at a focused point of impact, a bone can still be fractured. A final limitation is that the WE-FMEA is much like its parent FMEA, it is a tedious analysis; it is as time consuming as a system FMEA and requires a high level of knowledge about a variety of components and systems. Therefore, the WE-FMEA is not intended for application to every maintenance activity, only those activities taking place in the most complicated, congested or 'close quarters' parts of the facility where many types of hazards are co-located. This is a fitting limitation because in less congested areas of a facility, the primary hazards of the task at hand are expected to dominate the worker risk.

V. CONCLUSIONS

The WE-FMEA is a risk-based analysis tool that can support occupational safety assessment for complex work environments, such as magnetic or inertial fusion experiments, power plants, particle accelerators, or other complex, high-technology facilities. This new analysis method provides a systematic framework for assessing hazards that are proximate to the given task while existing approaches address only the hazards to be found within a given task. The WE-FMEA is to be used in concert with existing safety approaches, such as the JHA. The instrument calibration task used as a WE-FMEA example has shown that, with appropriate engineering component data and human injury data as support information, the WE-FMEA can be applied to fusion experiments and other facilities to estimate the worker risk from the secondary or 'peripheral' hazards. Secondary hazards can have the greatest influence on worker safety when the workers are following the JHA and adequately protecting themselves from the primary hazards of the task. Actuarial data from similar industries can serve as points of comparison to WE-FMEA results.

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