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Evolution of Safety Management Within the Scaled Wind Farm Technology (SWiFT) Facility Program

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Abstract

Since being commissioned in 2013, Sandia National Laboratories (Sandia) has operated the Scaled Wind Farm Technology (SWiFT) Facility for the Department of Energy Wind Energy Technologies Office (DOE/WETO), conducting and leading wind energy research in the areas of advanced simulation, improved wind plant performance, development and testing of advanced wind turbine rotors, and the critical next steps towards national grid integration, modernization and energy security. The SWiFT Program partners with academia and industry in providing valuable and unique research capabilities in areas such as turbine-to-turbine interaction and wake imaging using its three research-modified Vestas V27 wind turbines, two research instrumented meteorological towers, and integrated research capabilities and infrastructure co-located with Texas Tech University's National Wind Institute at the Reese Technology Center in Lubbock, TX. In the six years that the facility has been in operation, the SWiFT Facility program has evolved as a DOE moderate hazard facility through programmatic improvements and lessons learned from operational safety events.

As this unique site moves into the next decade of research and service to the wind energy industry, this research facility's safety management systems can provide insight into the areas of operations management and systems safety within a government research environment. The management of the SWiFT Facility transitioned from an 'island' of research separate from the parent Sandia complex in Albuquerque, NM to management of a research facility integrated with the Labs. Moving from relative isolation in developing a safety management system, the SWiFT Facility staff now have extensive reachback to subject matter experts and resources, and have built a safety management system framework from the ground up. Dramatically shifting its culture from one of solving environmental, health and safety problems in isolation due to a perception of the uniqueness of wind energy systems, to one of safety ownership and transparency, the SWiFT Facility robustly teams to find win-win solutions and sustainability in its safety systems and safety management.

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Wind Energy Research at the Department of Energy

With more than 60,000 wind turbines presently in use in 41 states, Guam, and Puerto Rico, and at least another 10,000 forecast to be installed by 2030 (Reuters, 2017), wind plant (wind farm) owners and operators are continuously seeking to generate the most power from their plants, and keep their operating costs as low as possible. The average age of installed wind turbines (capacity) in 2018 was seven years, and at the current rate of new installations and existing upgrades and retrofits, that average will increase to 14 years in 2030 (Froese, 2019). Naturally, as wind turbines age, the cost of keeping them operating increases (i.e. routine maintenance, troubleshooting, component replacement due to failure or wearing out). A recent analysis conducted by IHS Markit (2018) indicated that operations and maintenance (O&M) expenses for wind power assets will cost the industry about $7.5 billion annually by 2021. Further, the study also indicates that O&M costs average between $42,000 and $48,000/megawatt (MW) during the first 10 years of a wind turbine's operations, and that U.S. wind farm owners are expected to spend over $40 billion on O&M over the next 10 years (IHS Markit, 2018). This increase in O&M costs are subsequently leading wind plant operators to focus more and more on performance optimization.

This is where government-sponsored, industry-focused research into wind plant performance can help to dramatically lower the O&M costs of current and future wind plant operators. The U.S. Department of Energy's (DOE's) Energy Efficiency and Renewable Energy (EERE), Wind Energy Technology Office (WETO), and DOE national laboratories in particular, lead the nation's efforts to accelerate the deployment of wind power technologies, improve performance, and lower costs (Pelsoci, 2010). The research provided to industry by the DOE complex of national labs has had several key influences on the growth and sustainability of the wind energy industry in the United States. Most notably, these include:

- Research leading to increased reliability levels of wind turbines, which has reduced the commercial risks and financing costs; and,
- Development of analytical modeling, engineering databases, test protocols, and test facilities that have allowed turbine designers to move away from trial-and-error methods and large safety factors intended to avoid frequent turbine failures (Pelsoci, 2010).

The U.S. DOE now supports seven wind laboratory and testing facilities nationwide, all of which are available for industry use with the goals of helping industry to increase reliability, improve efficiency, and reduce the cost of wind energy (DOE/EERE/WETO, 2017):

- Lawrence Livermore National Laboratory (California)
- Pacific Northwest National Laboratory (PNNL) (Washington)
- Sandia National Laboratories (Sandia) (New Mexico)
- Idaho National Laboratory (Idaho)
- National Renewable Energy Laboratory (Colorado)
- Argonne National Laboratory (Illinois)
- Oak Ridge National Laboratory (Tennessee)

Together with two state-sponsored labs - Clemson University in South Carolina and the Massachusetts Clean Energy Center - these research institutions focus on a number of important areas to provide valuable data to wind plant manufactures and operators:

- Advanced manufacturing (innovative construction methods, combined with workforce

training to enhance U.S. global competitiveness)
- High-performance computing (systems that simulate complex phenomena to advance understanding of wind energy and technologies)
- Resource characterization (wind resource data collection to help optimize wind energy performance)
- Grid integration (testing facilities to help ensure reliable integration of wind energy into the electric grid)
- Field testing (testing turbine designs in the natural operating environment to optimize performance and improve reliability and efficiency)
- Drivetrain testing (dynamometers to validate wind turbine drivetrains to reduce downtime, improve reliability, and lower costs)
- Blade testing (validate wind turbine rotor blade design, performance, and durability through research, testing, and certification) (DOE/EERE/WETO, 2017)

The expertise and capabilities that the DOE and state labs offer enables a diverse portfolio of renewable and wind energy research. The primary benefit of this is that projects such as the DOE's Atmosphere to Electrons (A2e) research initiative (which targets significant reductions in the cost of wind energy through an improved understanding of the complex physics governing electricity generation by wind plants) can bring together a collaboration of scientists from the laboratories, industry, and academia to conduct systems-level research and advanced high-fidelity modeling to gain an understanding of wind plant operating environments (DOE/EERE/WETO, 2020).

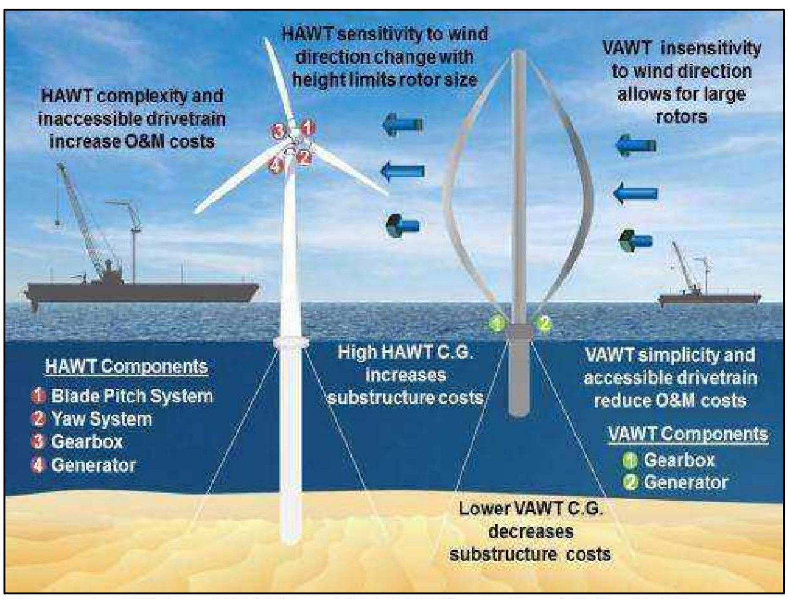

Figure 1. Offshore HAWT and VAWT illustration (SNL, 2018)

Federal- and state-sponsored wind energy research currently focuses on two primary types of wind turbines: the horizontal axis wind turbine, or HAWT, and the vertical axis wind turbine, or VAWT (Figure 1). HAWTs use a set of airfoil blades that rotate around a horizontal axis similar to an airplane propeller, while blade rotation on VAWTs occurs around an axis perpendicular to the ground (Hui, Cain, & Dabiri, 2018). Wind turbines are designed to be used in both onshore and offshore applications. Federal research into using the VAWT design goes back to the early 1970s, when Sandia began conducting VAWT research at its Albuquerque, NM location (Figure 2). Sandia experimented with increasingly larger VAWTs used for technology transfer through the 1970s, and began development of a research-only 34-meter, 500 kW VAWT in 1984 at the U.S. Department of Agriculture (USDA) wind test site in Bushland, Texas (at the time the 34-meter machine was the largest VAWT in the world) (Figure 3) (Galbraith, 2011; SNL, 2016). The Bushland site ceased its DOE-funded research in 2011, and the research moved to the Reese Technology Center in Lubbock, Texas under Sandia's leadership. The vision for what became the Scaled Wind Farm Technology (SWiFT) Facility grew from the need to perform experimental work in turbine-to-turbine interactions and to evaluate innovative rotor technologies. The areas of research at the SWiFT Facility now include aero-acoustics, advanced wind plant controls, wind flow diagnostics, hybrid power systems. aero-elasticity and structural health monitoring using embedded sensor systems.

Figure 2. Sandia National Labs 5-meter VAWT (Berg, 2016).

Figure 3. DOE Sandia/USDA 34-meter VAWT Test Bed (Berg, 2016).

The Scaled Wind Farm Technology (SWiFT) Facility

Figure 4. Reese Technology Center and the SWiFT Facility, Lubbock, TX (Google Earth, 2020).

The Scaled Wind Farm Technology (SWiFT) Facility was completed in 2013 in Lubbock, TX on the site of the former Reese Air Force Base, now called the Reese Technology Center (Figure 4). While its location is a 5-hour drive for researchers based in New Mexico, Reese was very attractive for a wind energy research facility for several reasons. First, Reese is the home to Texas Tech University's (TTU's) National Wind Institute (NWI), conducting critical research in the areas of energy systems, atmospheric measurement and simulation, and wind engineering (NWI, 2020). By co-locating the SWiFT Facility with the NWI, the research conducted by Sandia and TTU benefit by leveraging each institution's physical and data collection assets. Secondly, the open campus of Reese (i.e. the existing airfield) reduces the impact that terrain and physical structures (buildings) can have on incoming wind flow, meaning that the facility's three research modified, three-bladed Vestas V27 model wind turbines can operate with unimpeded wind flow, at consistent speeds while generating data. Most importantly, the location's 6.8 meters-per-second average wind speed, and prevalent wind direction from the south (Kelley & Ennis, 2016) provides consistent conditions for conducting wind energy experiments 365 days per year. The resources at the Reese location are also consistent with an off-shore wind environment, making the site useful for that growing area of research.

The SWiFT Facility (Figure 5) enables research and development to not only support DOE-sponsored wind energy research, but also private and public sector organizations such as universities, industry companies, and other national laboratories. SWiFT was developed using a unique partnership between DOE, Sandia, Vestas Wind Systems, Texas Tech University's National Wind Institute (NWI) and Group NIRE (Berg et al., 2014). The primary objectives of the SWiFT Facility are to:

- Reduce turbine-to-turbine interaction and wind plant underperformance
- Develop advanced wind turbine rotors
- Improve the validity of advanced simulation models

The DOE/Sandia managed SWiFT facility is the first of its kind to use multiple wind turbines to measure how wind turbines interact with one another in a wind farm. The design of the SWiFT Facility allows for rapid, cost-efficient testing and development of transformative wind energy technology, with specific emphasis on improving wind plant performance. Advanced testing and monitoring at the site has already shown how larger wind farms can become more productive using the site's scaled modeling and proof of concept. The term 'scaled' within the name of the SWiFT Facility refers to the design of the facility to use the relatively small size of the heavily modified Vestas turbines (27-meter rotor diameter, 33.5-meter hub height) to replicate the performance and behavior of much larger megawatt-scale turbines. By having this scalability, research can be conducted with less complex experiments, an increased ability to instrument blades and the turbine itself, reducing testing time and cost, and allowing for minimal restrictions on intellectual property (Berg et al., 2014).

Figure 5. SWiFT Facility Lubbock, TX (Windpower, 2015).

A key Sandia regional research partner is the National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory (NREL). For over 40 years the NWTC, located on the Flatirons Campus in Golden, Colorado (Figure 6), has conducted research across a spectrum of wind energy engineering disciplines, such as atmospheric fluid mechanics and aerodynamics, dynamics, structures, and fatigue, power systems and electronics, and wind turbine engineering applications (NWTC, 2011). The NWTC's unique wind energy research and testing capabilities include:

- Design review and analysis
- Software development, modeling, and analysis
- Advanced controls development and testing
- Certification and design evaluation testing
- Highly Accelerated Life Testing
- Transmission and grid integration
- Wind resource assessment

Researchers at NREL's Flatirons Campus work with the DOE, universities, independent systems, and regional transmission organizations to provide data and models to assist in managing wind grid system integration.

Figure 6. NREL Flatirons Campus research facilities for wind energy, water power, and grid integration (Schroeder, 2016).

Standing Up a New Research Facility and the Learning Organization

Construction of the SWiFT Facility began in 2013 and was completed in early 2014, at which time the Sandia SWiFT team began commissioning activities. Commissioning of a wind turbine involves testing all components of the wind turbine once installed for verification of subsystem functionality, particularly electrical and turbine control, as well as overall turbine operability per manufacturer specifications (Wind Energy: The Facts, 2020). The SWiFT turbines are an original equipment Vestas design, with modified generators (the SWiFT Facility turbine generator is 300 kW vs the original 250 kW – with the ABB power converter limited to 200 kW). The generator and converter modification enable variable speed blade pitch operation via the turbine controller and specialized controller software. Since these modifications altered the original operating parameters of the turbines, the Sandia team also had to develop unique user manuals (operating, electrical, mechanical, erection, and commissioning testing) derived from Vestas operating manuals. In addition, the DOE and Sandia imposed numerous safety-related requirements being a new research facility, including the completion of an operating envelope document, technical work documents and procedures for work activities at the site, and job safety analysis (JSA) documents for site construction and commissioning activities. All of this activity was occurring in a project environment with a limited budget and an optimistic scope and schedule, which may be expected when developing a first-of-a-kind research facility. In addition, when researchers begin designing a new research facility, they primarily focus on the research capabilities desired, but may lack the expertise to conduct risk assessments and stakeholder engagement interviews. These latter two functions serve to integrate the desired research capabilities with a comprehensive assessment of the necessary safety management framework.

In 2014, one of the three turbines at the SWiFT Facility went into an overspeed condition (rotor rotational speed exceeding turbine design limitations), leading to a failure of the rotor and subsequent destruction of the turbine. Debris thrown as the rotor began to fracture led to a number of analyses to assess future potential risk, including the initiation of a safety basis process, a standalone hazard analysis, a debris analysis, and several hazard analyses (failure modes analysis, failure modes and effects analysis, what-if/checklist analysis, qualitative risk analysis) (Stirrup, 2016). This ultimately led to the determination that SWiFT was a moderate hazard facility, meaning that "hazards which present considerable potential onsite impacts to people or the environment, but at most only minor offsite impacts" (DOE, 1994).. In addition to the replacement of the failed turbine, a comprehensive root cause analysis (RCA) was conducted by Sandia, which imposed a number of programmatic corrective actions. To be truly effective, and to understand the mechanism of system failures and identify potential weaknesses within the system, a failure modes and effects analysis (FMEA) performed early on in the design process, especially where redundancy is needed for critical components of the system (Birolini, 2017), can be extremely valuable in developing initial engineered safety controls. The direct and contributing factors leading to the 2014 accident at SWiFT revealed that although a significant amount of requirements development and analysis went into the turbine control systems, project development actions were continuing in parallel with operation of the machines. Corrective actions pertaining to engineered safety, operating procedures, hardware safety systems, site safety, and the turbine control system were indicative of a continued understanding of interactions between the system and the users. As design, construction, and commissioning of a new research facility commences, iterative analyses ensure that design changes that affect system safety do not occur in a vacuum. As a component of program management, system safety management formally ensures that safety is intentionally designed in by designing out hazards, or at a minimum reducing the risks of mishaps (Ericson, 2005).

After all corrective actions were implemented, the SWiFT Facility initiated a documented management self-assessment (MSA) to ensure that all corrective actions met the intent of the RCA. Once the MSA was complete, a rigorous independent readiness review (IRR) was conducted of the SWiFT Facility to validate the effectiveness of corrective actions implemented, and to develop a report of readiness for approval to begin normal operations. The site was assessed to have implemented all corrective actions as recommended by the causal analysis report, the failed wind turbine was replaced and commissioned successfully, and the site was granted approval to begin normal operations and research at the site in 2017. The SWiFT team continued to strengthen internal controls while conducting research at the site, such as procedures and turbine manuals. The facility commenced with a major research initiative called the Wake Steering Campaign, jointly executed with NREL. The goals of the experiment were to demonstrate the capability of wake (the disturbed air that results from wind passing through a wind turbine rotor) steering control to improve total wind turbine array (wind farm) power production (Herges, 2018). The Wake Steering Experient ran through the end of 2017, and the site continued to bring the remaining turbines online through mid-2018.

In 2018 while troubleshooting a turbine system, an employee experienced a mild electrical shock. While the severity of the shock was minor, the subsequent RCA revealed several areas associated with the turbine safety systems, along with implementation of work planning and controls (the process of identifying, planning, approving, controlling and executing work at a DOE facility) (DOE, 2011a). The causal analysis conducted in 2014 primarily identified weaknesses in turbine safety control systems and organizational effectiveness, whereas the 2018 causal analysis recommended strengthening training, additional rigor on work documentation, continuing efforts to improve software parameter changes, intrateam communications, and turbine electrical system design for operability (user-centered design). Coming out of the 2014 event, the system: meaning the people, procedures, hardware, software, and support structure, had not been considered holistically. Out of the hazard analyses, the project then developed a list of remedial actions, process controls, influenced design, plan risk mitigations, and designed in preventative measures using a systems-based approach (Gullo & Dixon, 2018). Drawing from principles of nuclear safety basis at this point, which is a deeply-rooted at Sandia and throughout the DOE nuclear complex, provided a path to safety sustainability at the SWiFT Facility. As Goble (2008) writes, within the human performance – performance objective topic area, the behaviors of individuals within a team support a safe and reliable facility, with each person taking responsibility and committing to performance improvement:

1. Frequent and concise communication – inform management and coworkers of present and potential issues and provide recommendations to address them.
2. Make conservative decisions and verify assumptions before acting.
3. Anticipate problems and mitigate them before and during tasks being performed or supervised.
4. Always be on the lookout for conditions that can lead to human error and eliminate them.
5. Reinforce defense strategies that mitigate error consequences.
6. Always focus on the task at hand to reduce the likelihood of error, and include strategies such as self-check, peer checking (two-person verification), and mentoring/coaching to encourage personal accountability and responsibility (R2A2 - roles, responsibilities, authorities, and accountabilities).
7. Follow procedures and technical work documents, and correct procedural deficiencies before starting or continuing the task.
8. Integrate and practice team skills to improve performance.

While returning to research at the SWiFT Facility was very important, especially for a facility that had still not been brought fully on-line (i.e. all three machines operating and producing energy to allow for research), the need to continually push for safety improvements existed. The most important feature of sustainable safety is to always be looking for latent conditions and ways to prevent their manifestation within the system. The primary mechanism for accomplishing this is to implement a robust risk identification and management plan. Safety management focusing on continuous improvement within the overall level of safety while measuring performance, analyzing processes and becoming an integral part of a facility's operational management activities site culture (Müller & Drax, 2014). Moreover, implementing safety management principles requires the establishment of processes which allow the control of safety risks, and introduce the concept of acceptable level of safety within the operational tempo of reestablishing normal site operations. Besides assisting an organization to better understand its current level of safety, a safety management system (SMS) also communicates that level of safety to all stakeholders, it prevents incidents and accidents, and it improves overall communication, morale, and productivity (Lowe, 2008).

Within the Department of Energy, system safety is defined as "a facility structure, system, or component of which the preventative or mitigative function is a major contributor to defense in depth or worker safety as determined from hazard analysis" (DOE, 2011b). DOE G 414.1-2B further defines system safety as "a DOE structure, system, or component, including a primary environmental monitor or a portion of a process system, the failure of which could adversely affect the environment, safety, or health of the public or workers." The DOE implements system safety through integrated safety management (ISM) (Figure 7), the objective of which is to "integrate safety into management and work practices at all levels, addressing all types of work and all types of hazards to ensure safety for workers, the public, and the environment" (DOE, 2011b). Referring to the ISM's seven guiding principles and five core functions (Figure 8), the first core function, define the scope of work, sets in motion the necessary rigor and processes that need to occur in order for a program, project, or activity to be planned and executed safely.

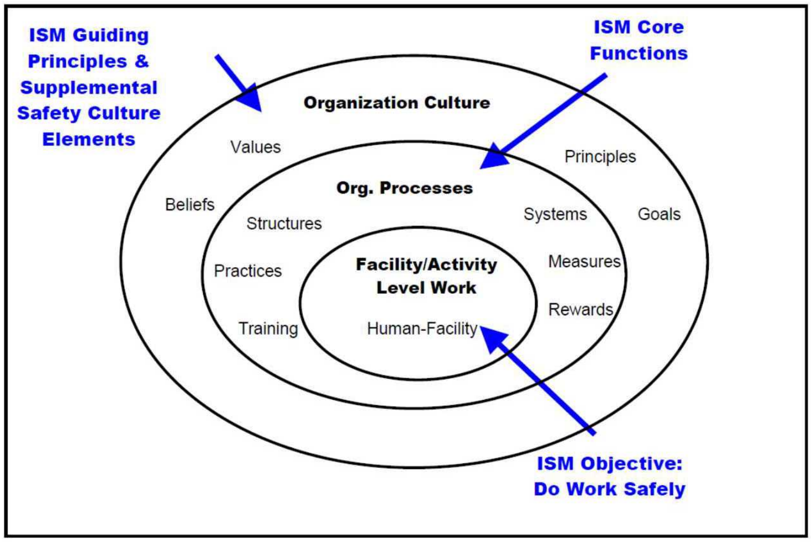

Figure 7. DOE ISM relative focus of attention by organization level (DOE, 2011b).

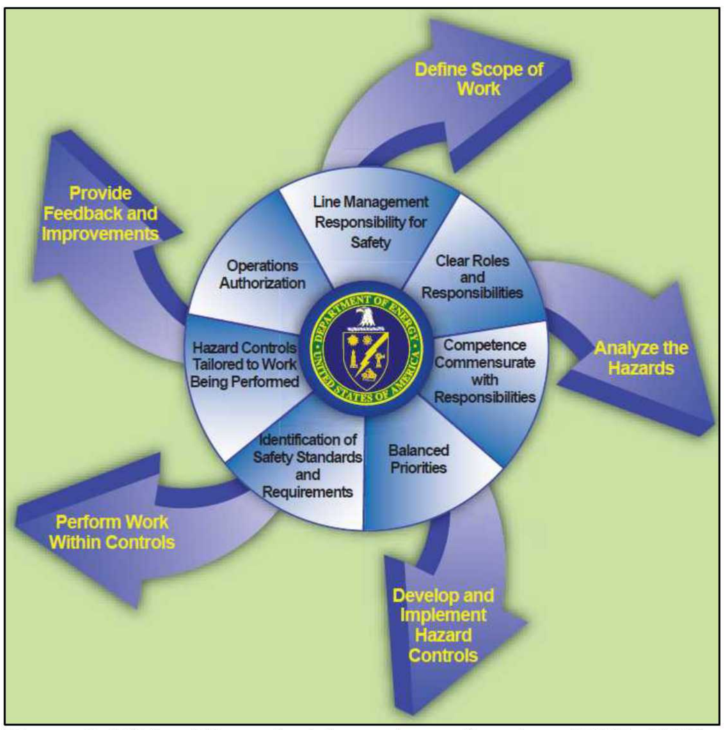

Figure 8. ISM guiding principles and core functions (DOE, 2012).

DOE's ISM (DOE, 2011a) considers site-specific factors, conditions, analyses, and processes to include:

- The types of potentially hazardous work at the site, such as operations, maintenance, construction, and research and development
- Results of design studies, safety analyses, hazard reduction analyses, and risk analyses
- All types of hazards at the site, to include chemical, physical, ergonomic, environmental, and transportation

Another of the core functions of DOE ISM is the analysis of hazards. Sites identify and categorize hazards, then develop an understanding of the potential for each hazard to affect the health and safety of workers, the public, and the environment (DOE, 2011a). This is followed by the development and implementation of hazard controls using engineered, administrative, and personal protective equipment (PPE) measures, the third ISM core function (DOE, 2012).

One of the primary tools that the DOE uses for facility safety is the safety basis and accompanying safety analysis processes. The safety basis is the documented safety analysis and hazard controls that provide reasonable assurance that a DOE facility can be operated safely in a manner that adequately protects workers, the public, and the environment. Following the 2018 event, the SWiFT Facility safety basis document was revisited and revised with a team comprised of safety basis engineers and SWiFT technical experts. This safety analysis process used to develop the original and updated safety basis accomplished four significant objectives for the facility:

1. It provided a systematic identification of both natural and man-made hazards associated with the SWiFT Facility;
2. It evaluated normal, abnormal, and accident conditions;
3. It enabled the team to derive and update the hazard controls necessary to ensure adequate protection of workers, the public, and the environment, and demonstrate their adequacy; and,
4. It defined the characteristics of the safety management programs necessary to ensure the safe operation of the facility (DOE, 2014).

To engineer in safety, a project team must first identify the possible hazards of a new system through collaborative hazard analyses, and identify those states that can lead to an accident or incident (Stapelberg, 2009). With qualified experts representing all systems and specialties relevant to the new facility, a safety case is prepared that relates to an assurance that the system is as safe as reasonably possible.

An operational and safety control framework, which included the effective and timely identification and management of risks was slow to develop at the SWiFT Facility. Primarily because the initial focus was on getting the infrastructure in place, establishing critical relationships with partners, managing budget and schedule, and all by a small team of researchers. This all required incredibly strong project management skills and the ability to work within rigid DOE requirements. In retrospect, time was not taken to fully engage SMEs to help develop and inform effective, transparent, and sustainable (evolving) operations and SMS frameworks due to the need to get the turbines modified, tested, and the site operational. The remote location of the SWiFT Facility, a 6-hour drive from Albuquerque, meant that the overall time commitment for even the smallest task from a team member at Sandia required at least 2 days of time commitment from that individual to complete (the drive out, perform the task, and the drive back). The remote location of the facility also made it difficult to coordinate reachback to appropriate organizational environmental, health and safety (ES&H) and systems safety subject matter experts (SMEs) for consultation. This spectrum of project and safety management (Figure 9) is foundational for sustainability to take hold.

Figure 9. Underlying and latent factors that can influence project success.

Establishing and maintaining a comprehensive SMS throughout the system life cycle is the most cost-effective way to control risks in a project as well as a primary method of preventing an accident (Bahr, 2014). Implementing robust and deliberate system safety early on in a project provides the means to develop a risk management strategy for requirements pertinent to a new research site based on potential and actual hazard identification and analyses (Gullo & Dixon, 2018). Conducting an initial hazard analysis in the early conceptual stage of a new research facility allows a project team to use that information to help guide the emerging design respective of safety requirements throughout the engineering design process (Stapelberg, 2009). When designing and constructing a new research facility, the project lead can understandably be under pressure to get the facility built and operational, while at the same time putting together a team to conduct the research and daily operations and maintenance (O&M). This makes it even more critical for that point person to have the necessary knowledge and safety expertise available as leverage to influence design, and to help manage stakeholder and customer expectations.

The 2020s and SWiFT's Capabilities

The SWiFT Facility has gone through many changes over the course of two years since the 2018 electrical shock event. The present focus is not simply satisfying and closing out corrective actions, but instead placing a strong emphasis on the effectiveness and sustainability of corrective actions, and of instilling a culture within the project team that would seek to continually improve the effectiveness and performance of safety management. Team leadership used an operational excellence management system (OEMS) model (Figure 10) to:

- help manage the large number of corrective actions,
- to engage the team and drive ownership in the vision for the facility and research program,
- to add structure and meaning to a reconstruction of the overall project and safety management systems, and
- to help keep a well-defined set of tasks in progress, rather than implement a total site stand-down.

Sandia Wind Energy Technologies leadership has involved the entire team in establishing a shared vision for the wind research organization. This has provided a beacon to which the team can steer towards, and is serving to harness and channel energy and excitement for the future of the SWiFT Facility and research initiatives, and to provide direction and motivation for all stakeholders (Lutchman, Evans, Maharaj, Al Hashemi, & Al Hashemi, 2015).

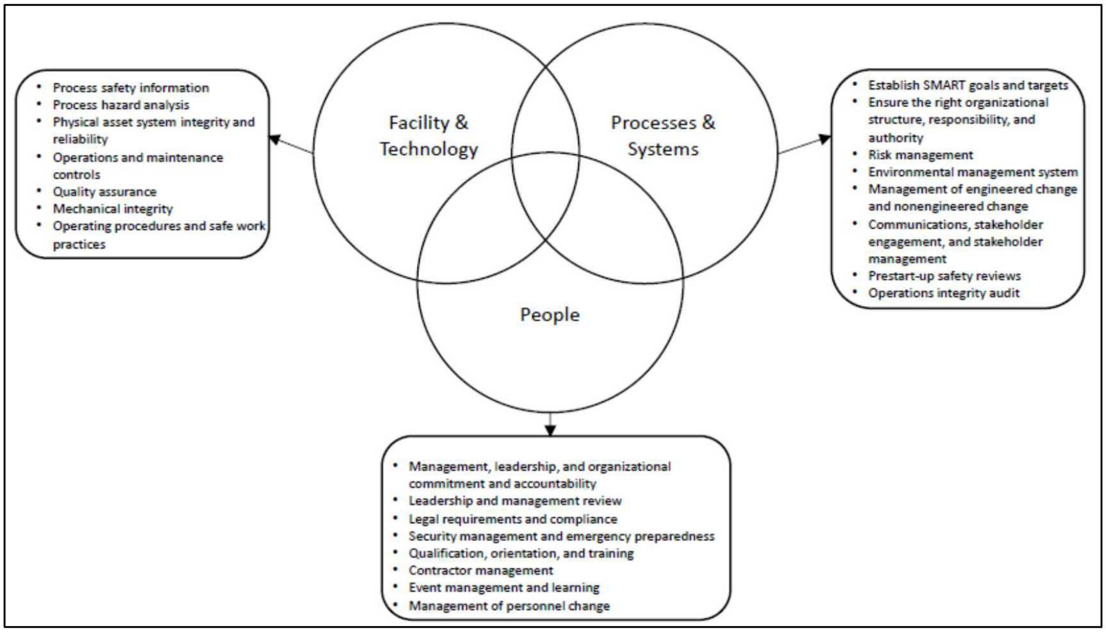

Figure 10. Categorized OEMS elements (Lutchman, Evans, Maharaj, Al Hashemi, & Al Hashemi, 2015).

Enabled by greater reachback into Sandia, and with Sandia fully committed to providing the necessary resources to the site, a multidisciplinary team of ES&H professionals and systems safety SMEs travelled to the site in 2018, and a second team comprised of a differing set of SMEs travelled to the site in 2019. SMEs from emergency management, facilities electrical safety, LOTO, industrial hygiene, and fall prevention and protection were included, and evaluated what was working well within each of their respective specialties, and what areas required additional attention and guidance. Topics noted by these teams included confined space, electrical safety (dedicated circuits and suggested modifications to better implement LOTO), and tower rescue (incapacitated worker/climber – need for emergency response drills). Nearly all procedures, policies, and technical work documents were either partially rewritten, or completely rewritten in order to better integrate DOE and Sandia safety requirements, and to make them more user-friendly (to encourage their use and understanding). New procedures were developed for the turbine safety systems and software, and a dedicated hardware-in-the-loop (HIL) system was fabricated in order to test software deployments offline before deploying in the field on the turbines. A configuration management procedure was implemented, with an engineering change notice (ECN) process to initiate, analyze, and implement design changes to the turbine systems. The ECN process also serves as a record for future SWiFT teams on why and how engineering decisions were made, especially those that were not implemented. New procedures are reviewed holistically to ensure that they are not introducing new, unintended hazards, such as the requirement to climb the tower multiple times to accomplish a task.

To strengthen the SWiFT project and safety culture and safety ownership by all team members, structured weekly meetings have been established, and each meeting begins with a safety topic contributed by different team members. A wind industry electrical SME was contracted by the wind group in order to provide analyses and recommendations on high voltage system improvements and modifications, and several significant modifications and retrofits were implemented as a result, greatly reducing the potential exposure to arc flash incident energy for the wind turbine technicians and engineers. Having an industry expert as a part of corrective actions also allowed for the synergy of a research site with industry standards and best practices. Most importantly, the MSA and IRR were conducted collaboratively with the safety engineering community, which instilled a greater understanding of the moderate hazard designation and requirements, and subsequently higher quality safety analyses and documentation.

As the facility continues to evolve in its R&D mission, it is expected that there will still be areas that require improvement, but with the level of management and SME engagement, and cognizance about operational and system safety, the anticipation is that any further actions will be minor in nature. With a functional management system now in place, the SWiFT team recently installed the National Rotor Testbed (NRT) rotor (Figure 11) onto one of the turbines. The anticipated NRT project uses a specially designed subscale wind turbine blade that has wake similar to a modern, commercial size blade (Kelley, 2015). Generating a scaled wake will allow for testing of new technologies at less cost than using a full-scale wind turbine test facility. Sandia and Texas Tech University have also begun a joint project to connect the SWiFT wind turbines to the adjacent Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM), which will open up a completely new realm of collaborative research opportunities at the Reese Technology Center in the areas of microgrids, cybersecurity, distributed energy, and grid modernization. This work is being performed using the rigors of system safety engineering, with multiple levels of review and design approvals, and with the input of electrical safety and high voltage engineers, as well as with the industry electrical SME to ensure continuity with industry standards and practices, and as another set of eyes to ensure that all LOTO and user-centric considerations are made.

Figure 11. SWiFT Facility rotor installation (Riley, 2020).

Conclusion

System safety's goal is to make sure that hazards are detected to the fullest extent possible, and that protective measures are introduced early enough in system development to preclude design changes later in the system life cycle (Ericson, 2005). Since its inception in 2011, its construction and commissioning in 2013, a major safety event in 2014, and an electrical safety event in 2018, the Scaled Wind Farm Technology (SWiFT) Facility has undergone the gamut of project starts and stops, corrective action implementation, operations scrutiny, and team accomplishments. The focus of facility staff now is on resiliency, safety and sustainability, integrated into all decisions, analyses, and infrastructure upgrades and modifications. As a sustainable research facility, SWiFT now manages risk integratively to reduce accidents and improve performance, continuously monitoring the facility and process risks, and engaging in planning and proactive prevention to minimize incidents if and when they do occur again (Lee, 2018). The SWiFT Facility is quickly becoming a center-of-excellence within the U.S. Department of Energy's renewable energy research complex, a one-of-a-kind facility that acts as an outdoor wind tunnel for developing and testing new wind energy technologies and models, complimenting the research capabilities at the DOE's other eight locations across the country. System safety allows its operators to determine what can go wrong before it does, and institute controls to prevent those occurrences or reduce the probability of occurrence through hazard identification and mitigation (Ericson, 2005). Implementing elements of system safety has proven to be highly effective in the design, construction, testing, and operation of machines and systems in multiple disciplines such as aviation, aerospace, product manufacturing, and information technologies, so its application to wind energy research and new technology development is timely. With any new research facility, risk management must begin at the front end by addressing risks. Beginning with program risk (the overall risk to the project or program), technical risk (a subset of program risk), and design risk (a subset of technical risk) (Gullo & Dixon, 2018), the program/project manager must be equipped and empowered to employ numerous tools in order to identify, analyze, and mitigate risks throughout the lifecycle of a system. Assessing and managing risk is multifaceted, and requires the program/project manager to have a keen understanding of the component, the equipment, the system, and the individuals and teams who design and operate the system, and the environment of the system (technological, organizational, physical) (Yves, 2012). At the SWiFT Facility, moving into the 2020s is viewed with excitement and a renewed sense of safety and program growth.

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