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Tacit Knowledge Involvement in the Production of Nuclear Weapons:

A Critical Component of a

Credible US Nuclear Deterrent in the 21st Century

by

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Biography

Lieutenant Colonel Stephanie J. Buffett is a U.S. Air Force nurse assigned to the Air War College, Air University, Maxwell AFB, AL. She graduated from Purdue University in 1981 with a Bachelor of Science degree in Nursing, from Indiana University in 1988 with a Masters of Nursing Science, and from Uniformed Services University of the Health Sciences in 2003 with a Masters in Public Health. She taught for Indiana University School of Nursing, Indianapolis, Indiana prior to entering the Air Force. She has served in a variety of leadership positions and is a graduated squadron commander.

Abstract

Preservation of nuclear weapon tacit knowledge has not previously been linked to maintaining a credible US nuclear deterrent. President Obama's 2009 Prague speech committing the US to seek a world without nuclear weapons, has yielded two policy debates: the necessary arsenal size and force configuration required to have a credible deterrent while following the Road to Global Zero nuclear weapons, and the potential feasibility of getting to zero due to shortcomings in monitoring and verification. Absent from these debates, and indeed missing from the discussions altogether, is the role of tacit knowledge about nuclear weapon design and development on the road to zero. The relationship between tacit knowledge and credible nuclear deterrence has yet to be examined. US weapons designed to last 10 years are now over 20 years old and projected to be maintained for several more decades while the last of the scientific community having actual experience designing and testing nuclear weapons are preparing for retirement. If both explicit and tacit knowledge are required in the knowledge transfer process, and all those with process knowledge retire, there will be no one left who has the tacit knowledge required for building a nuclear weapon in a timely fashion. In this paper, tacit knowledge is defined along with the relevance of tacit knowledge in creating a nuclear weapon and the need for nuclear tacit knowledge preservation and transfer in today's environment. An assessment of the Lawrence Livermore National Laboratory suggests that neither the working environment nor the data management system in place currently fosters tacit knowledge transfer or capture. Recommendations are offered as steps to enhance tacit knowledge preservation and transfer to support a credible nuclear deterrent through the next several decades until such time as the Road to Global Zero comes to an end or takes a critical detour.

Introduction

I shall reconsider human knowledge by starting from the fact that we can know more than we can tell… Michael Polanyi

President Obama's 2009 Prague speech committing the US to seek a world without nuclear weapons, has yielded two policy debates: the necessary arsenal size and force configuration required to have a credible deterrent while following the Road to Global Zero nuclear weapons, and the potential feasibility of getting to zero due to shortcomings in monitoring and verification. Absent from these debates, and indeed missing from the discussions altogether, is the role of tacit knowledge (TK) about nuclear weapon design and development on the road to zero.

This paper, therefore, will address the increasingly important question of how to preserve nuclear weapon TK in a time when no testing has occurred in 20 years. The United States may plausibly forget how to make nuclear weapons before getting to any numerical thresholds or before the decision of who will get rid of the last nuclear weapons first occurs. US weapons designed to last 10 years are now over 20 years old and projected to be maintained for several more decades while the last of the scientific community who have actual nuclear weapon design and testing experience prepares for retirement. If both explicit knowledge (EK) and TK are required in the knowledge transfer process, and all those with process knowledge retire, there will be no one left who has the TK required for building a nuclear weapon in a timely fashion.

The relationship between TK and credible nuclear deterrence has yet to be examined. Two positions quickly come to mind: either TK does or does not matter for the maintenance of a credible nuclear deterrent. For those who see the US nuclear deterrent purely as a political tool not to be relied upon for actual use, or at most as a defense against the homeland where reliability of each weapon is not central, TK is not important. The second position, that TK is important for a continued nuclear deterrent, also has two directions of thinking. One stance is that sufficient knowledge is effectively transferred through the generations of scientists due to advances in technology even without testing nuclear weapons. However, this paper will stipulate that TK is vital to the continuation of a safe, reliable, and effective nuclear deterrent, and provides evidence that it is in jeopardy.

This thesis will unfold by first examining tacit knowing as laid out by Michael Polanyi along with the relevance of TK about nuclear weapon design and development in creating and maintaining a credible nuclear deterrent. While focused on the role of TK in maintaining a credible US nuclear deterrent, this paper also provides insight into challenges faced by other nuclear states, and opposes the proliferation view that connects nuclear designs and material with iron-clad nuclear weapon competency.[1] Next, Lawrence Livermore National Laboratory (LLNL) is assessed against stated criteria to determine whether or not TK transfer is being fulfilled. Finally, this paper will recommend steps forward concerning TK to maintain a credible nuclear deterrent through the next several decades until such time as the Road to Global Zero comes to an end or takes a critical detour.

Tacit Knowledge

Understanding TK

Knowledge can be defined as a fact or condition of knowing something with familiarity gained through experience or association: acquaintance with or understanding of a science, art, or technique.[2] Knowledge is frequently divided into two primary forms: EK and TK. EK is codified and conveyed to others through language, symbols or mathematics. EK is communicated on paper, formulated into sentences, spoken, or captured in drawings and, in general, can be easily captured and shared. In contrast, TK is personal knowledge which embodies all things that one knows how to do but cannot explain. TK may be tied to the senses, skills in bodily movement, individual perception, physical experience or intuition.[3] The hallmark of TK is that it is passed from person-to-person where the sender may not be conscious of knowledge being conveyed and the receiver not conscious of the knowledge gained.[4]

TK comes from Michael Polanyi's theory on tacit knowing. Polanyi believed creative acts, and especially acts of discovery, were charged with strong personal feelings and commitments.[5] In contrast to the day's dominant position that science was "value-free," Polanyi argued that informed guesses, hunches, and imaginings were a part of exploratory acts motivated by personal passions.[6] Polanyi posited that tacit knowing was personal knowledge that one may or may not be aware of and yielded more knowledge than one could tell.[7] Further, he theorized that EK and tacit knowing were mutually exclusive. Polanyi offered the examples of riding a bike or swimming. While one may know how to accomplish the task, and can write steps required to accomplish the skill, putting every facet into words that can be replicated without experimentation is not possible.[8] Polanyi believed skill acquisition is passed from generation-to-generation by personal transmission and that the learner does not even explicitly recognize that s/he is acquiring the skill. Polanyi favored a master-apprentice model for thinking about science and discovery.[9] Increasingly, the greater scientific community has acknowledged the significance of TK. From the scientific realm, Harry Collins described TK as "knowledge or abilities that can be passed between scientists by personal contact but cannot be, or have not been, set out or passed on in formulae, diagrams, or verbal descriptions and instructions for action".[10]

Significance of TK in Nuclear Weapon Design and Development

Of course, two arguments are keen: 1) if TK is necessary, or relevant, in the creation of a nuclear weapon; and 2) thus, if TK is important in sustaining a credible nuclear deterrent without testing. Thinking in the early days of the Manhattan Project was that designing a nuclear weapon would occur quickly. Renowned physicist Edward Teller recalled being discouraged from joining the Manhattan Project at Los Alamos National Laboratory (LANL) because designing the bomb would be too easy. However, the LANL staff quickly grew into the thousands to accomplish the "multitude of apparently humdrum engineering tasks that the physicists had underestimated."[11] Donald MacKenzie and Graham Spinardi first proposed that TK was not only an essential component in creating nuclear weapons, but that the ban on testing nuclear weapons could create their accidental un-invention.[12] They theorized that TK played a major role in nuclear weapon development and supported this theory with evidence obtained from nuclear scientists, and how nuclear technology spread. [13]

In the 1990s, MacKenzie and Spinardi conducted interviews with LANL nuclear scientists who revealed that they could not codify all the necessary information required of designers because the environment was too dynamic with several scientists referring to the design process as an "art." Additionally, scientists discussed the "long learning curve" for new designers; even those with a physics background. The typical learning curve was five years to become useful and 10 years to be recognized as a fully experienced nuclear weapons designer.[14] Finally, scientists relied on computer modeling or "codes" to predict how the device would behave, yet judgment was paramount to determine which aspects of the codes to trust, not to trust, and how intervening variables such as temperature and age factored into performance.[15] Even with experienced weapon designers at the helm, the United States averaged six nuclear explosion tests during the development of a new nuclear weapon model and France reported requiring up to 22 tests during design development.[16]

Evidence that TK is not easily transferred in the making of nuclear weapons is found in the initial development of the Soviet and British nuclear programs. Following the two atomic bombs dropped in Japan in 1945, the US held a monopoly as the sole nuclear power. There was great surprise when the Soviet Union successfully tested nuclear material in 1949, several years earlier than had been projected. Unknown at the time was that the Soviet spies were transmitting US nuclear design and testing data as it was occurring. In June 1945, highly sophisticated Soviet scientists received detailed US plutonium implosion weapon descriptions, sketches and measurements and set out to copy the design. [17] Note that only EK could be shared in the form of documents and diagrams. So the question arises as to why it took another four years to develop their own bomb when they held the US-tested design in their hands. The likely answer is the Soviets only possessed the EK for making a nuclear bomb, and had to develop technological skills, or TK portion, on their own to resolve the bomb design problems.

A second case that supports the TK requirement for developing nuclear weapons is demonstrated by the British Nuclear Program. British scientists had great difficulties with their nuclear program in the early years despite involvement with portions of the Manhattan Project. With permission, the British copied the US Trinity-Nagasaki bomb design, and again their result took longer that the Manhattan project, five years in total, and yielded a device that used PVC tape as a remedy for gaps in the explosive lenses.[18]

The Soviet and British programs, and in fact all subsequent nuclear programs, took longer to produce initial results than the original 23-month Manhattan Project.[19] Each program involved hundreds to thousands of science staff and each faced substantial practical problems.

MacKenzie and Spinardi posed that the spread of nuclear weapon capacity following the Manhattan Project progressed more along the lines of re-invention than technology transfer. Further, they highlighted the importance of a close working relationship among the nuclear weapon niche specialists,[20] and concluded that TK appeared to be most important in the technical design phase of nuclear weapons but that the balance between TK and explicit knowledge are not conclusive.[21]

Environment for Nuclear Weapons TK Transfer

Consistent with Polanyi's ideas on transfer of knowledge are the modern day creation of community of practice (CoP). Etienne Wenger theorizes that a CoP is much more that participating in group activities. Each CoP develops a unique identity influenced by active individual participation yielding conflict and harmony that is intimate and political, and promotes competitive and cooperative aspects of participation. The CoP produces artifacts in the form of tools, procedures, stories and language that will be understood only within the CoP and at differing levels as a novice grows to expert.[22] Harry Collins proposed that even in the most advanced modern science, TK is a perishable, local phenomenon not widely diffused but the property of a relatively small group of people and transmitted hand-to-hand and face-to-face.[23] Both CoPs and scientific communities support a dynamic environment including lively sociological, scientific, physical, and personal influences over time as critical for TK transfer. Therefore, a loss of any component of the vibrant environment would put the unique TK at risk.

From the beginning of the US Nuclear Weapons Program, a key process was to refine new designs and understand yield of weapons through nuclear testing. In the 1960s, the shift from quantity to quality of weapons grew into a continuous cycle of modernization by building and replacing the weapons stockpile with newer designs.[24] Objectives during the years of unconstrained testing included new design, one-point safety, proof of concept testing, demonstration of performance under marginal conditions, and obtaining physics data related to design.[25] The modernization programs were achieved through a large cadre of scientists engaged in continuous research and development resulting in multiple warheads being fielded and replaced within a 15-20 year period.[26] This rich environment is exactly the type of setting Polanyi would have described as fertile for TK transfer.

To this point, the discussion has been on TK and the application to the development of a nuclear weapon in a robust scientific environment. Since the end of underground nuclear testing in 1992, the number of US nuclear weapons has decreased from over 20,000 warheads in 1990, to a New START Treaty figure of 1550 warheads by 2017. Along with the decreases in warheads has been the decrease in the number of nuclear scientists and their scope of practice, with maintenance as the goal for both the stockpile and scientists.[27] If TK in making nuclear weapons requires person-to-person knowledge transfer in a dynamic environment, then how does it occur today and is it at risk? To date this issue has not been studied.

The nuclear power plant industry is on a similar trajectory and presented as an industry that has acknowledged the importance of TK capture. While the nuclear weapon industry has national security and political ramifications not shared with the power plant industry, both are niche specialties and do safeguard nuclear material from cradle to grave from unauthorized access. Comparably, both are in a period of decreasing mission along with aging and decreasing numbers of nuclear scientists that allows one to draw parallels in actions necessary to preserve TK.

Preservation of TK in the Nuclear Power Plant Industry

Within the nuclear power plant industry, the International Atomic Energy Agency (IAEA) has recognized the threat of institutional memory loss of nuclear knowledge across the spectrums of education, institution and government. Due to the classified nature of their work, US nuclear scientists cannot share issues or concerns they are experiencing about the nuclear weapons programs with other nations; however, this is not the case for the nuclear power plant industry. In June 2004, the IAEA organized the first technical meeting with member states to develop guidance on the preservation of nuclear knowledge for nuclear power plant operations. Two of the primary benefits cited for integrated knowledge management were increasing the value of existing knowledge and collecting, developing, and integrating TK.[28]

In 2005, the IAEA held a Managing Nuclear Knowledge Conference including 24 countries and three international organizations which was devoted to the preservation of nuclear knowledge and knowledge transfer for power plant organizations. Three of the five themes focused on human resource and knowledge transfer; managing and preserving knowledge in the nuclear sector; and networking for education, training and knowledge transfer.[29] Of particular interest is that while organizations were taking different approaches, each had recognized the need to take action to preserve TK.[30] Interestingly, a key finding from this conference was the recognition that knowledge transfer in the nuclear power industry was a real and significant issue, not a "fad" or of pure of academic interest.[31] The case unfolding in Germany is noteworthy because of the decision to phase out all nuclear energy over the next 15 years. Germany is struggling with both the dramatic decline in nuclear science students and preserving the essential knowledge within the regulatory and technical support organizations. The German Federal Office of Radiation Protection is faced not only with a lack of expertise in the industry, utilities, and regulatory authorities, but maintains responsibility for continued operation safely until the last plant is closed.[32]

Unlike the nuclear weapon complex, the nuclear power plant industry has acted on the growing gap in nuclear knowledge expertise. A follow-up 2007 Managing Nuclear Knowledge Conference sponsored by the IAEA was held in cooperation with the European Atomic Forum, the Japan Atomic Energy Agency, the World Nuclear Association, the World Nuclear University and others to advance work begun in 2005. Over 100 papers were presented by 40 nations with the overall themes of preserving nuclear knowledge necessary to continue safely operating nuclear power plants.[33] While definitive solutions are still in the development and implementation stages, it is clear that the nuclear power plant industry has taken the first step in recognizing the critical nature of the growing knowledge gap in the safe handling of nuclear material. Conversely, to date neither the DOE nor the DOD has recognized the potential or actual loss of TK in the US nuclear weapons industry.

Criterion for Assessing TK Capture and Transfer at Lawrence Livermore National Laboratory:

Thus far, TK has been presented as relevant to nuclear weapon design and development and therefore important to the promotion of a credible nuclear deterrent. Transfer of TK may be all the more important given the shrinking nuclear weapon community where the scientists are segregated from other scientific communities due to national security issues. Additionally, the very activities that promote TK transfer in the form of creative application (i.e. design and testing) are restricted due to political constraints. A plan to capture, foster and preserve nuclear weapon TK would support the continuation of a credible nuclear deterrent and include:

a) A planned dynamic work environment to foster TK transfer in intimate, cross generational groups of scientists (i.e. master-apprentice or CoP model), and

b) A knowledge management system that recognized the importance of capture and preservation of TK.

LLNL is one of three National Nuclear Security Administration (NNSA) Laboratories whose reason for existence was to build, and now is to maintain, the US nuclear weapons explosive package, in partnership with the US Navy and US Air Force. Since 1994, LLNL has been held in a continuous loop of relying on the Stockpile Stewardship Maintenance Program (SSMP), a small portion of the full-cycle perpetual nuclear production and replacement program of earlier years, to preserve core nuclear intellectual and technical competencies.[34] Is it enough? In the next section, the above criteria are used to assess TK transfer and preservation efforts at LLNL to better understand TK as it relates to maintaining a credible nuclear deterrent.

Lawrence Livermore National Laboratory Case Study

LLNL Environment

Many changes in the environment have occurred in the last twenty years since the plethora of scientists engaged in designing and testing nuclear weapons. Changes presented will include the scope of work, the number and skill of scientists, and the recruitment and management of employees as they apply to an environment that fosters TK transfer.[35] The no-testing policy was the big change that drove the LLNL and all the National Laboratories to a new strategy of retaining already produced warheads indefinitely through the implementation of the SSMP. The scientists were directed to certify the stockpiles as a continued safe, reliable, nuclear deterrent. New venues were needed to keep scientists actively engaged and it was felt that advances in technology would keep the scientists "sharp" and capable of returning to nuclear weapon design if needed. Congress funded new technology in the form of the National Ignition Facility (NIF) at LLNL, the Dual-Axis Hydrodynamic Radiographic Test (DAHRT) Facility at LANL and the Z Machine at Sandia National Laboratory. The Advanced Scientific Computing Initiative (ASCI) provides advanced high-performance computing capability and modeling and simulation computer codes to support the SSMP. Although scientists now understand the underlying physics and diagnostics of why designs did and did not work, this knowledge adds little to sustaining capacity to design or build a nuclear weapon. Interestingly while the NIF and ASCI have increased confidence in certain areas of the design space, it is acknowledged that computer modeling is definitely different than under- and above-ground testing and being able to better understand the past does not necessarily transfer to being predictive of the future. Clearly, the application of science, technology and skill requirement is different for design verses maintaining existing nuclear weapons.

Within just a few years of the moratorium on testing nuclear, scientists began to voice concerns of knowledge degradation at LLNL's sister laboratory. MacKenzie and Spinardi reported on a panel of 22 leading and retired nuclear weapons scientists gathered at LANL in 1993 who were concerned about the atrophying of certifier's judgment. The scientists were concerned that modified weapons would be certified in the future based on little or no supporting data by scientists who had no practical knowledge of the weapon. There was worry that untested weapons might be certified to please political or military leaders.[36] It may be that the scientists were unable to articulate the risks of continuing in a scientific environment that offered no practical experience but knew it intuitively – a classic example of TK.

Over time, concern grew that scientists skill might atrophy, but all attempts to allow nuclear weapon design were consistently overshadowed by concern for political ramifications.

Although Congress created the Reliable Replacement Warhead (RRW) program in 2004 to improve the reliability, longevity and certifiability of existing weapons and component parts, funding was cut when the National Nuclear Security Administration (NNSA) introduced a multi-year plan to introduce new warhead designs. One of the stated benefits of the program was to maintain scientific interest and skills, but the critical nature of skill maintenance (TK) was not highlighted. The political entities were concerned with signals such a project would send and refused to fund "new designs."[37] In 2008, the Department of Energy (DOE) and Department of Defense (DOD) published *National Security and Nuclear Weapons in the 21st Century* again calling for the RRW to be funded in part to address the serious brain drain in the national nuclear program due to a 25% reduction in the NNSA workforce from 1995 to 2008 along with half of nuclear lab scientists being older than 50 in 2008.[38] Politically the idea of "new design" was unacceptable and ultimately Congress did not fund the RRW without any real consideration of the impact on the nuclear scientific community.[39] President Obama's announcement of the road to zero in 2009 killed any hopes for implementing the RRW program in the future.[40] Again, not recognized was the potential negative impact in the US nuclear deterrent by nuclear weapon intellectual capital degradation.

Among the acknowledged challenges noted by the 2006 Defense Science Board *Report on Future Strategic Strike Skills* was the serious loss of critical strategic skills over the next decade, the difficult challenges to maintain a safe and reliable stockpile as well as fewer nuclear experts with testing experience. What is most important here is while the loss of nuclear scientist and physicists was acknowledged, plans to mitigate or remedy were not offered.[41] Today the LLNL employs about 6,000 scientists, 40% less than the 10,000 employed in the 1980s. Incredibly, "somewhat" less than 20 scientists remain on the LLNL payroll including both full-time and retired/retained personnel that have actual nuclear test experience.[42] This alone poses significant challenges for fostering TK transfer.

Finally, the new technology at LLNL provides an attractive workplace, including experimental laboratories, which is important in recruiting young scientists, allowing LLNL to develop an extensive post-doctoral program. While LLNL has many university partnerships, retaining the highest level scientists remains difficult. There is concern that once the novelty of the NIF wears off that the SSMP will not be stimulating. Further, it is hard to entice young scientists to remain at the laboratory when they can go to the private sector and earn several times the laboratory salary. Complicating the issues further is a lack of a master-apprentice relationship conduit due to the best and brightest LLNL scientists being ushered to the management track and rewarded with higher salaries. A program to financially reward superior science is a recent promising step, but it is still too early to assess the impact.[43]

In summary, technology-based stewardship, physics and computing has dramatically changed the scientists' professional environment from the original design and testing of nuclear weapons. The foundational assumption in a period of no nuclear testing was that a technology solution could effectively replace practical experience, and was faulty. When the error was recognized, politically acceptable solutions were not offered and the overall degradation in both numbers of nuclear weapon design scientists and experience ensued. The nuclear science community has voiced concern of knowledge atrophy and is decreasing at an alarming rate with little promise for expanding in the future. While the LLNL has impressive facilities, the environment does not appear to be a natural setting for the robust, dynamic scientific interchange that fosters TK transfer.

Lawrence Livermore National Laboratory Knowledge Management Efforts

In November 2012, LLNL senior management leaders were asked if they were at all concerned that there might be a knowledge gap between those scientists having nuclear test experience and the current generation. The response was that retirement interviews “covered it all”. When specifically asked if TK transfer was a concern, the response “No, we capture everything on video or through interviews.” Clearly, they were not aware of the nature of TK, the potential significance, or application. Still there are knowledge management efforts underway with the focus of capturing and preserving information.

LLNL employees a database management system to capture electronic records, interviews, and plans and drawings that are accessible to researchers. Additionally, there are currently three primary venues available to capture knowledge and/or retain nuclear skill sets. Retiring scientists are interviewed with the goal of preserving knowledge that was not written down in research papers or reports. The aim is to document in writing or in videos information, including procedures and processes that would not otherwise be captured. Questions might include: “What was involved in the test series?” or “Why did you take this path?” or “Tell me more about the data you recorded for this test.” These interviews have taken place for the last ten years. On first look, this would seem to be an attempt to capture TK, but these interviews at best fills in EK gaps.

A second long-standing effort of retaining and growing designers' skills includes a robust tri-laboratory technical peer-review of scientific work between the design labs. The endeavor serves both as a historical archive and current research repository as well as outlet to share work and receive recognition for scientific accomplishments. While the interviews and peer-review collaboration preserve EK, the necessary environment to capture and transfer TK has not been developed.

A final significant engagement process is involvement of LLNL nuclear scientists with foreign nuclear weapons programs. Many of the scientists are part of the intelligence community contributing significantly to different National Intelligence Estimates regarding foreign weapons programs. This active role helps maintain nuclear weapon skills by bringing scientists together to assess weapon design and focus on alternative threats. Of the current activities taken by the LLNL to preserve nuclear weapon knowledge, working on foreign weapons programs is most likely to fulfill the requirements for TK transfer.

One promising post-Cold War attempt was a joint laboratory-corporate sector adventure. Interested in pursuing advanced physics and nuclear research and development (R&D), the national laboratories sought collaboration with civilian industry that had shifted significant funds away from corporate R&D. There was hope for effective partnerships as LLNL could conduct the R&D then hand-off to corporations for production. Unfortunately, conflict of interest, national security issues, and LLNL not being able to directly complete with private industry (make a profit), brought an end to the vision. Such a venture would have kept LLNL scientists more fully engaged in the creative processes required for R&D. Had this adventure included a university arm, the full complement of novice and experienced scientists working to solve interesting nuclear science problems, it would likely have produced the ripe environment for TK transfer and preservation.

LLNL has employed a database management system in an attempt to preserve nuclear scientists' information. The system appears to lack integration of information to transform it to knowledge, significantly without consideration of a tacit component. Current actions taken to preserve knowledge at LLNL do not appear to be sufficient to sustain nuclear TK indefinitely. Given the age of the remaining nuclear weapons designers, time may be quickly running out.

Conclusion and Recommendations

The impact of TK loss in making nuclear weapons on the US nuclear deterrent has not been previously brought to the forefront. While Global Zero may be a goal for some and a pipedream for others, the reality is that US nuclear weapons are at a 30 year low and expected to go lower. Additionally, the nuclear weapons community is faced with a vanishing population of scientists with nuclear weapon testing experience. In today's environment, TK is not only vital to a credible US nuclear deterrent but may offer telling insight into challenges faced by other nuclear states as well as proliferators seeking a nuclear capability. LLNL has clearly sought to engage scientists through advanced technology and taken steps to capture scientific data. However, these actions do not appear to project a robust environment conducive to TK transfer or capture. In spite of this, steps can still be taken to preserve nuclear TK, and transfer it through the generations of nuclear scientists, to ensure the US maintains the intellectual capital necessary for a persistent, credible nuclear deterrent.

The foundational recommendation is to conduct a classified study investigating threats to, or actual loss of, TK throughout the nuclear weapons industry. In conducting research for this paper, several areas lack elaboration due to classification level. A study in the classified domain would flush out any pressing gaps having national security implications and solidify an all-inclusive plan to preserve nuclear weapon TK. Areas to consider for inclusion in a comprehensive plan:

- A complete knowledge management program across all national laboratories focusing on critical elements of knowledge transfer and that has been shown to capture TK. New techniques, including virtual environments, show promise in converting some TK to EK for easier capture and transfer.

- Investigate legal venues, ameliorate blockers, and champion increased collaboration between the national laboratories, universities and the private sector. Of vital importance is the ability to articulate to policymakers the criticality of creating this collaborative triad.
- Develop or strengthen the practice of financially rewarding superior science by keeping top scientists in the laboratory in lieu of "promoting" and redirecting top performers toward management positions. Create an official duel track advancement system with commiserate pay scales.
- Implement a mentorship program to include mentoring activities between laboratories. Emphasize person-to-person lifelong learning with recognition of experience over conventional education that is based on learning objectives.[44] Furthermore, make active, effective mentorship one criteria for superior performers to facilitate establishing mentorship as part of the organizational culture.
- Consider implementing high-reliability organization principles and processes. High-reliability organizations are characterized as succeeding under trying circumstances, performing daily a number of highly complex and technical tasks in which they cannot afford to "fail."[45] These organizations have many processes built-in to promote TK transfer, and adopting critical features of high-reliability organizational structure would support all other efforts to preserve nuclear TK.

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. For concerns over North Koreas third nuclear test and lateral nuclear proliferation see: Allison, "North Korea's Lesson."
2. Merriam-Webster. *Knowledge.*
3. Von Krogh et al., *Enabling Knowledge Creation*, 83.
4. London School of Economics. "Tacit Knowledge."
5. Infed. "Michael Polanyi and Tacit Knowledge."
6. The term tacit knowledge comes from Michael Polanyi (1891-1976), a Hungarian born polymath who received doctoral degrees in both medicine and physical science before making significant contributions on crystal structure and reaction kinetics. Polanyi studied under Albert Einstein before emigrating to Britain in 1933 where Polanyi served as Professor of Physical Chemistry at the University of Manchester (1933-1948). During which time, he turned his attention to philosophy and then became Professor of Social Sciences at Manchester (1948-1958). Polanyi's position was likely inspired by and he may have been reacting to the time in which he lived with the backdrop of fascism and communism.
7. Polanyi's explanation was that one attends to whatever is of interest "focal attention", but to do so require that we integrate much that is not of our attending "dwell in." In other words, while attention is focused on a specific point, task or occurrence, a vast amount of additional information is taken in and processed unconsciously which contributes to the overall acquisition of knowledge.
8. Polanyi, "The Structure of Tacit Knowing."
9. Mullins, Phillip. Michael Polanyi expert, interviewed by author; 2 November 2012.
10. Collins, "Tacit Knowledge, Trust and the Q of Sapphire," 72.
11. Coutard, "The Abolition of Nuclear Weapons," 181-183.
12. MacKenzie and Spinardi, "Tacit Knowledge, Weapons Design, and the Invention of Nuclear Weapons," 89.
13. MacKenzie and Spinardi, "Tacit Knowledge, Weapons Design, and the Invention of Nuclear Weapons," 49.
14. Evidence that does not support the NTH Country Experiment, conducted at Lawrence Livermore in 1967, conclusion that two newly graduated physicists with no access to, or knowledge of classified information could design a viable nuclear weapon. Frank, "NTH Country Experiment."
15. MacKenzie and Spinardi, "Tacit Knowledge, Weapons Design, and the Invention of Nuclear Weapons," 59-63.
16. Arms Control Association. "The Future of Nuclear Weapons Without Nuclear Testing."
17. MacKenzie and Spinardi. "Tacit Knowledge, Weapons Design, and the Invention of Nuclear Weapons," 68-77.
18. MacKenzie and Spinardi, "Tacit Knowledge, Weapons Design, and the Invention of Nuclear Weapons," 68-73.
19. Younger, *The Bomb*, 13-32.
20. MacKenzie and Spinardi, "Tacit Knowledge, Weapons Design, and the Invention of Nuclear Weapons," 63.

21. Coutard, "The Abolition of Nuclear Weapons," 181-183.
22. Wenger, "Communities of Practice. Learning, Meaning, and Identify," 55-56.
23. Collins, "The TEA Set: Tacit Knowledge and Scientific Networks," 183-184.
24. Department of Defense, *Nuclear Matters,* 4-5.
25. Arms Control Association, "The Future of Nuclear Weapons Without Nuclear Testing."
26. Department of Defense, *Nuclear Matters*, 5.
27. Department of Defense, *Nuclear Matter,* 6.
28. Kosilov, "Knowledge Preservation for Nuclear Power Plants."
29. International Atomic Energy Agency, "Managing Nuclear Knowledge."
30. The Tennessee Valley Authority which operates five nuclear power plants and has implemented a knowledge retention process due to a projected 70% retirement of the workforce between 2002 and 2013. Included in the process were steps to assess and prioritize threatened critical knowledge and skills, develop and implement plans to capture or adapt to critical knowledge loss, and monitor and evaluate action plans success. A key lesson learned was that greatest risk of knowledge loss was in the specialized technical positions requiring problem solving strategies. The Chilean Commission for Nuclear Energy (CCNE) is an independent State organization created as the legal authority to protect public nuclear interests and develop science and nuclear technology throughout Chile. The CCNE reported on implementing a human resource management plan in response to an anticipated loss of more than 40 of the country's 160 professional and director staff between 2005 and 2015. These retirements come on the heels of an already depleted workforce due to encouraged retirement of all government employees over the age of 70 years in 2003. While acknowledged that remedial actions are urgently needed to mitigate risks and sustain institutional viability, the CCNE was still in the planning phase for an overall knowledge management system in identity, harvest, preserve and transfer nuclear knowledge. The British Nuclear Group, responsible for 18 nuclear power plant sites throughout the United Kingdom, acknowledged that the knowledge management field had changed in emphasis from being heavily weighted in capture and dissemination of skills and experience to how knowledge is created and shared. This appears to be a clear shift from explicit to tacit knowledge capture. The Group used experienced plant operators and engineers to develop a safety scenario database as a training tool for future training.
31. Petri, "The German Approach to Nuclear Knowledge Management."
32. Petri, "The German Approach to Nuclear Knowledge Management."
33. International Atomic Energy Agency, "International Conference in Knowledge Management of Nuclear Facilities."
34. Department of Defense. *Nuclear Matters*, 51.
35. Much of following information comes from my interviews with Dr. Craig Wuest, Global Security Principal Directorate, LLNL, and my visit to the LLNL in November 2012.
36. MacKenzie and Spinardi, "Tacit Knowledge, Weapons Design, and the Invention of Nuclear Weapons," 91-92.
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