Repairing Credibility: Repositioning Nuclear Weapons Knowledge after the Cold War

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Introduction

What does it mean to say that a nation has a credible nuclear capability? One seemingly obvious answer is testing: between 1944 and 1992 the United States alone detonated more than 1000 nuclear weapons (US Department of Energy, 2000), and images of the mushroom cloud, combined with the horrific scenes caused by the bombing of Hiroshima and Nagasaki, were the signature scientific and technological demonstrations of the twentieth century (Gusterson, 1996: 131-164; Masco, 2006: 44-98). Similarly, states like India, Pakistan, and North Korea have sought to establish themselves as credible nuclear powers on the world stage by conducting nuclear tests. In recent years, however, as the major nuclear powers have observed a moratorium on nuclear testing, they have had to grapple with the question of how to maintain technical credibility and aging weapons stockpiles while also projecting confidence in their weapons without the dramatic demonstration testing provided.

The major role nuclear weapons continue to play in the global geopolitical arena often overshadows the reality that the credibility of nuclear deterrence is built upon a massive (and expensive) infrastructure of expert practices, institutions, and facilities for designing, testing, and building nuclear weapons. This infrastructure serves to produce

not only stockpiles of nuclear weapons, but also cadres of scientists and technologists who possess a body of technical expertise unique to nuclear weapons. Beginning with the Manhattan Project, and continuing throughout the Cold War, the US built thousands of nuclear weapons, and in the process created a vast, nation-spanning system for producing them known as the 'nuclear weapons complex.'

The early 1990s marked the beginning of a major crisis of credibility for this system: as the Soviet Union collapsed, orders for new weapons systems were cancelled by the first President Bush, and in 1992 President Clinton signed legislation halting US nuclear weapons testing. The US became a signatory to the Comprehensive Test Ban Treaty (CTBT) in 1996 (US Department of Energy, 2000). The end of testing raised the most concern at the time, but in some ways the end of weapons design and production had a bigger impact: plants were shut down and many skilled workers lost their jobs. Within a few short years, the U.S. had lost much of its capability to produce new weapons. Actors both within and outside the weapons community began mobilizing resources to ensure that these developments did not threaten the credibility of the U.S. nuclear deterrent.

In this paper we examine two attempts to repair the credibility of the U.S. nuclear weapons capability in the post-Cold War period: The Stockpile Stewardship Program and the Reliable Replacement Warhead (RRW) program. Stockpile Stewardship is a program that was successfully proposed to Congress and the Clinton administration in the mid-1990s. It has focused on maintaining weapons expertise through a huge investment in non-nuclear experimental facilities and state-of-the-art computing and simulation

capabilities. Stockpile Stewardship is the current organizing concept of the U.S. nuclear weapons complex, and the primary source of funding for the weapons laboratories.

RRW was also conceived in the mid-1990s, but did not gain organizational and political traction until after 2000. This program seeks to replace stockpile weapons with warheads that can be designed and produced without nuclear testing and that will remain stable in the stockpile for long periods of time. RRW was funded briefly in the 2005-2007 time period before Congress cut the program, but it continued to have significant support within the defense and foreign policy establishments early in the Obama administration (Grossman, 2009).

In order to capture the structures and discourses that mark off the credibility of the nuclear weapons complex, we draw on both qualitative and quantitative content analysis of nuclear weapons program documents and interviews with 13 current and former administrators, weapons designers, and engineers at Los Alamos National Laboratory (LANL).[1]

Sociotechnical Repair

While many studies have explored the success, failure, and overall contingency of sociotechnical systems,[2] less attention has been paid to how systems are maintained over time, particularly in the face of systemic crises and exogenous change. We use the concept of 'repair' as part of an analytic framework for understanding these issues (Henke, 2000a, 2008; Sims and Henke, 2008). Our use of the term draws on its use in ethnomethodology, where repair is a way of maintaining social order (Schegloff, 1992, 1997; Schegloff, Jefferson, and Sacks, 1977; Collins, 1990). Though most prior work on

repair has focused on how meaning is preserved in conversation, we examine a broader set of practices we call *sociotechnical repair*. This includes the techniques actors use to maintain the practices, institutions, and technologies that form a system like the nuclear weapons complex.[3] We suggest that sociotechnical systems and institutions, just like conversations, are dynamic processes that must remain under constant repair in order to maintain their coherence and boundaries.

This conception of repair encompasses three types of practice. Conversation analysis studies most commonly focus on *discursive repair*, the attempt to maintain the cultural frames we use to describe and understand the world. Our everyday usage of the term 'repair' usually refers to *material repair*, or the fixing of things that may be broken or worn out. Finally, *institutional repair* is aimed at repairing social structures and practices. These types of repair are interrelated and are used together in any specific instance of sociotechnical repair: for example, a chemical company that has experienced an accident may make institutional and material repairs to prevent a recurrence of the accident, while simultaneously using these repair efforts as part of a discursive effort to repair the company's public image (Henke, 2000a, 2008; Graham and Thrift, 2007). Breaking down these complex practices into three basic types of repair provides a useful set of dimensions for analyzing the diverse strategies that actors use to maintain their interests in and control of a sociotechnical system.

We also describe repair in terms of the scope of the change it encompasses. Repair always involves changing some system elements in order to stabilize others. However, the balance between change and stability can vary. At one end of the continuum, *maintenance* involves changes that largely preserve the current structure of

practices, organizations, and power. This type of repair is often favored by those with a vested interest in the current structure of a sociotechnical system. Maintenance can encompass relatively routine efforts, such as repainting a bridge or providing training courses to improve employee skills. It can also cover more significant changes that involve a great deal of effort and cost. For example, Henke's (2000b, 2008) work on repair in the farm industry in California shows that state and industry players were often willing to invest enormous resources to maintain existing structures in the face of diverse crises.

On the other end of the repair continuum, *transformation* is a repair strategy that seeks more radical change in existing structures and practices, in order to maintain what actors see as core elements of a system. Transformative repair is often pursued as a last-ditch effort in the face of grave threats to institutional survival, or by critics of a system who wish to reshape it in light of their own ideals and interests. Typically, transformative repair is more difficult to enact, because it works against existing practical and institutional structures. For instance, in the aftermath of Hurricane Katrina, attempts to restructure the system of flood control in New Orleans and the Gulf Coast have been limited by economic, infrastructural, and cultural factors (Sims, 2007a; Henke, 2007; Bijker, 2007; Wetmore, 2007) – this despite the fact that there is near-universal agreement that the sociotechnical system is broken.[4]

The end of the Cold War was perceived as a major crisis for the nuclear weapons complex. Besides leading into episodes of repair, such breakdowns are interesting because they force people to articulate the hidden sources of social order and meaning in institutions. The conversations and debates that led to Stockpile Stewardship and RRW

articulated specific visions of where nuclear weapons expertise had come from within the Cold War nuclear weapons complex, and where it might come from in the future.

The nuclear weapons complex is unique among large sociotechnical systems in the direct role it plays in global projection of U.S. power, and has a distinct place in history as a focal point of the Cold War. However, historians have noted that, in other respects, it is just the most dramatic symbol of a larger trend toward 'big science' and complex military technology during the 20th century (Hughes, 2003; Galison and Hevly, 1992). As such, we believe it can serve as a useful exemplar for repair in large, complex sociotechnical systems, which play an increasingly dominant role in social and political life in the 21st century.

Credibility and Repair

Although repair mechanisms in the nuclear weapons complex may be typical of large sociotechnical systems, the primary locus of repair is distinctive. Due to the direct relevance of nuclear weapons knowledge to geopolitical power, the technical credibility of weapons scientists plays a particularly prominent role in underwriting the legitimacy of the entire complex. Stockpile Stewardship and RRW can best be understood as repair efforts directed at this credibility.

Credibility is a fundamental topic in social studies of science and technology, where it has been seen as the primary mechanism for generating collective knowledge out of individual beliefs. In science, the basis for a factual claim is usually only directly observed by a small number of people - say the scientists and technicians who conduct an experiment. These individuals may have reason to believe their results are valid, but these

beliefs do not become knowledge unless they are accorded credibility by a wider scientific community. This is a cultural and institutional process, in which everything from the documented experimental methodology to the personal reputations of the researchers can come into play (Shapin, 1995).

Within core scientific communities, credibility is usually embedded in personal interactions and relationships of trust, and a consensus body of knowledge evolves over time. In these circumstances, explicit discussion of credibility is rare (Shapin, 1994; Shapin, 1995: 269-270; Collins, 1992:51-78). It is when scientists seek to justify their claims to other professional communities, or to the public at large, that credibility requires explicit attention. In such circumstances, formal warrants of credibility become more important – professional credentials, institutional affiliations, demonstrations of methodological rigor, peer review, etc. (Shapin, 1995; Giddens, 1990; Jasanoff, 1990; Gieryn, 1983, 1999). A general principle is that any time a community wants to deploy its consensus knowledge within a wider social context, significant effort may be required to establish the credibility of that knowledge.

Public demonstrations can also play a key role in securing credibility (Shapin and Schaffer, 1985; Latour, 1988; Henke, 2000b). For claims about the functioning of technological systems, testing often plays a particularly prominent role, as it has for nuclear weapons. During the Cold War, nuclear tests served as a key modulator of credibility for the nuclear weapons community (Gusterson, 1996; McNamara, 2001). Within the weapons community, they served to establish the professional status of designers, and they provided a dramatic demonstration to a wider audience that weapons scientists could be believed when they said weapons would work. However, a test is not,

in itself, a solution to problems of credibility: the test itself must be seen as having a connection to the deployed performance of a system (Pinch, 1993; MacKenzie, 1989; Sims, 1999). The infrastructure of the nuclear weapons complex, along with the expertise of weapons scientists, itself served to back up testing as a projection of credibility. The simultaneous end of testing and contraction of the nuclear weapons complex following the Cold War therefore created a profound crisis of credibility for the weapons community.

Credibility is also a key element of nuclear deterrence theory, in which it is discussed as the general 'quality of being believed' (Morgan, 2003: 15). [6] Specifically, in the game-theoretic schemata of deterrence, an adversary is deterred from attacking if they believe a nation (a) has a threatening nuclear capability, and (b) will use it if attacked (Morgan, 2003: 15-19; Powell, 1990).

Nuclear deterrence theory generally focuses on the credibility of threats to use nuclear weapons. But the technological elements of deterrence have also been analyzed in terms of credibility. For example, nuclear weapons analyst Stephen Fetter (1988: 69-71) draws a distinction between stockpile confidence and stockpile reliability: reliability is the measurable likelihood of weapons working properly, and confidence is whether nuclear weapons scientists and policymakers believe they will work. Fetter argues that confidence, rather than reliability, is the key to deterrence:

> If American leaders are convinced of the reliability of their weapons, and Soviet officials, observing this confidence, are also convinced of the potency of the U.S. arsenal, then the requirements of deterrence are satisfied independent of the actual reliability of the weapons (Fetter, 1988: 70).

Fetter's framework covers two key interfaces where credibility must be established across social distances. First, scientists – confident in their own knowledge – have to establish credibility with national political leaders. These leaders must then convey confidence in their nuclear arsenal to leaders of other nations to establish the credibility of their nuclear deterrent. In this paper, we do not attempt to address the complete geopolitical context of nuclear deterrence. Rather, we focus on how weapons scientists maintained their own confidence in nuclear weapon performance after the Cold War, and how they worked to establish credibility with the immediate customers of their work: the military and the Department of Energy. We consider the larger political context primarily in terms of how it is invoked within this institutional context.

By focusing on this context, we position our analysis at an intermediate level between the scientific community and the realm of public discourse, examining how credibility is established at the level of sociotechnical systems and institutional politics. At this level, neither personal trust nor formalized institutionalized mechanisms can fully explain the dynamics of credibility. This makes it an ideal level for observing how credibility is established and repaired through diverse interactions among social, material, and discursive resources.

Credibility and Tacit Knowledge

The nuclear weapons community's struggles to cope with the major institutional changes that followed the Cold War were well documented in a number of sociological and anthropological studies conducted in the 1990s. Among the most important of these

was Donald MacKenzie and Graham Spinardi's (1995) sociological examination of tacit knowledge in the development of nuclear weapons. Tacit knowledge is knowledge that is difficult to capture or codify, but can be transmitted effectively through shared experience within a common cultural context (Collins, 1995: 51-78).

MacKenzie and Spinardi drew on weapons scientists' own descriptions of how their knowledge was built and sustained in order to advance their argument that tacit knowledge is essential to the production of nuclear weapons. At the time, nuclear weapons scientists were quite adamant that their knowledge could not be fully codified, that it was deeply embedded in the process of designing and testing nuclear weapons, and that it could not easily be preserved or transmitted in the absence of testing and its associated cycles of sociotechnical activity (Mackenzie and Spinardi, 1995; Gusterson, 2001; McNamara, 2001: 236-273). These concerns led MacKenzie and Spinardi to speculate that nuclear weapons might literally be 'uninvented' if their design and testing were halted for long enough.

MacKenzie and Spinardi's paper makes an argument about the essential nature of nuclear weapons knowledge. They claim that tacit knowledge of a certain kind, embedded within a certain context – that of nuclear weapons testing and production – is constitutive of nuclear weapons expertise. They further speculate that if this context were to be disrupted for a significant length of time, the tacit knowledge required to make nuclear weapons might simply cease to exist, or at least lose its validity. This argument emphasizes the conservative implications of tacit knowledge for social change.

Our focus on credibility leads us to consider the tacit knowledge involved in weapons work in a different light. We are more interested in understanding how weapons

knowledge is mobilized to advance the interests of the weapons community than in making claims about its essential nature. The argument the nuclear weapons community made about tacit knowledge in the 1990s served a rhetorical purpose. While it may have accurately described Cold War weapons knowledge, it also served to make the case that weapons testing and production should continue. This paper shows that the weapons community's descriptions of its own knowledge have continued to evolve since the end of the Cold War, sometimes in ways that are not consistent with the conservative tacit knowledge argument.

Credibility in the Cold War

The Cold War Production System

During the Cold War, the nuclear complex was organized around three interlocking activities: design, testing, and manufacturing of nuclear weapons. These activities were enabled by, and served to reproduce, an infrastructure consisting of three main elements: a stockpile of nuclear weapons, a testing capability, and a weapons manufacturing capability. These activities and infrastructure elements were the key elements that backed up the complex's institutional credibility. They were also the basis for the social organization of the nuclear weapons community, in which various communities of practice had particular roles and interests. These communities included weapons designers and engineers;[7] non-nuclear component engineers; test site scientists, engineers, and technicians; manufacturing engineers and technicians; missile system contractors; military liaisons; and many others.

These elements were integrated and reproduced over time via two ongoing cycles of activity.[8] The shorter *experimental cycle* focused on the testing of experimental nuclear devices with the primary goal of refining computer codes and improving knowledge about weapons physics. The longer, less frequent *weapons development cycle* involved the design, testing, and manufacturing of weapons systems for the nuclear stockpile. The cycles were thoroughly intertwined: they employed many of the same personnel, and any given test could be implicated in one or both.

The weapons development cycle was the main context in which weapons experts from the laboratories interacted with the military – the immediate 'customers' for nuclear weapons designed at the laboratories. This process was overseen by a 'Project Officer Group' consisting of representatives from the military and the Department of Energy, including personnel from the design laboratories (U.S. Department of Energy, 1984: 12). This joint body defined system requirements and provided general oversight of the development process, and was a key venue for interaction between military and technical personnel. This provided a key mechanism for evaluating and transmitting the credibility of weapons scientists beyond the boundaries of the nuclear weapons complex.

Capability-Based Deterrence

As with many aspects of social order, the sources of an institution's credibility are rarely articulated when that credibility is felt to be secure. It is not surprising, then, that the nuclear weapons community began to develop an explicit discourse about its credibility toward the end of the Cold War. This discourse revolved around the notion of 'capability-based deterrence,' a concept developed by a number of weapons program

managers at Los Alamos and elsewhere, but most clearly articulated by Sigfried Hecker, the director of Los Alamos National Laboratory from 1986 to 1997. As Hecker explained in our interview with him, capability-based deterrence is the idea that:

> It is the labs *per se* that provide the deterrence, not the bombs. Bombs can be overcome with newer designs or countermeasures, [but] the Russians will never be able to overcome our ability to evolve and develop new technological capabilities.[9]

In 1988, Hecker elaborated on the role of credibility in this view of deterrence, using arguments very similar to those quoted above from Stephen Fetter:

> Crucial to any successful policy of mutual nuclear deterrence is the belief beyond reasonable doubt of national leaders that their own and their adversaries' nuclear forces are survivable, are deliverable, and will function as intended. This belief does not rest on any technical knowledge on the part of the national leaders. It rests on assurances given to those leaders by scientists and this assurance requires that these scientists have credibility with their leaders. This confidence comes from the technical expertise we call nuclear competence (Hecker, 1988: 5-6).

Hecker positions the 'three DOE nuclear weapons laboratories' as the 'unique and fragile technology base' for nuclear competence (Hecker, 1988: 6).

Repairing Credibility: Stockpile Stewardship

Perception of crisis

Following the end of the Cold War, the experimental and weapon development cycles suddenly ended. Between 1989 and 1992, the Rocky Flats production plant was

shut down for environmental violations, President Bush announced that the U.S. would stop producing new warheads, and Congress passed the Hatfield-Exon-Mitchell amendment halting nuclear testing (McNamara, 2001: 3; Ackland, 1999: 215-227).

Around 1990, there was recognition within the design laboratories that the weapon development cycle would never come back in its original form, but this was not immediately treated as a crisis. It was not until after 1992, when the experimental cycle stopped, that managers and scientists at the weapons laboratories began to react with a sense of alarm. Los Alamos director Hecker attended a meeting in September 1992 where he learned that President Bush intended to sign the Hatfield amendment. In our interview, he recalled that he 'came back from that meeting and tried to impress people that our world had changed.' But the design community argued that it would be impossible to maintain the safety and reliability of the stockpile indefinitely without testing, and initially was not interested in considering alternatives (see also McNamara, 2001: 239-241).

The concept of stockpile stewardship originated in a series of workshops with laboratory managers held by DOE Assistant Secretary of Defense Programs Vic Reis beginning in 1993. The key elements of the program were codified in a 1995 Department of Energy document, *The Stockpile Stewardship and Management Program: Maintaining Confidence in the Safety and Reliability of the Enduring U.S. Nuclear Weapon Stockpile* (U.S. Department of Energy, 1995). Though it discusses a range of issues, the document's focus is on how to retain the technical expertise necessary to constitute a credible nuclear deterrent. The central argument is that under post-Cold War conditions,

the nuclear weapons laboratories need more, not less, funding to maintain their capabilities.

The key problems the document identifies are the end of testing and the end of production of new weapons. The end of testing is posed as a challenge to the ability to maintain confidence in the nuclear stockpile. Nuclear testing, the document argues, 'provided data sufficient to assess and maintain confidence in the safety and performance of the stockpile weapons.' Testing did so by allowing 'unambiguous verification of the effects of design features, material changes, or safety issues that could not be adequately calculated or tested in other ways.' This verification was crucial because, the document acknowledges, nuclear weapons knowledge is 'incomplete.' Therefore, it argues, maintaining confidence in the stockpile without testing will require extra effort to fill in 'gaps in our physics knowledge' and 'holes in the data' relevant to weapon performance.

The end of the production cycle is problematized primarily in terms of aging, of both weapons and people. The document points out that, without new weapons entering the stockpile, the average age of the stockpile will soon be older than it has ever been. Because of the lack of experience with aging, it argues, 'we cannot predict with certainty when age-related changes affecting weapons safety or reliability will occur,' but 'we must anticipate they will arise more frequently as the weapons retained in the enduring stockpile age to and beyond their original 20- to 25-year design lifetimes.' Without production, the document suggests, weapons knowledge might face similar difficulties: because the weapons laboratories will have 'an aging staff with actual experience in designing, testing, and producing nuclear weapons, the knowledge and skills base unique to nuclear weapons will atrophy.'

Discursive Repair

The concept of capability-based deterrence had already posed weapons knowledge as the central aspect of nuclear deterrence, but had stated that it could not be maintained without testing. Stockpile Stewardship's discursive innovation was to argue that weapons knowledge could maintain its credibility outside of this original sociotechnical context. This allowed Stockpile Stewardship advocates to use the rhetoric of capability-based deterrence to justify an even more central role for the design laboratories: without testing, the abstract knowledge of weapons scientists, divorced from its original context, would be the sole source of confidence in the stockpile:

> Without nuclear testing, confidence in the U.S. nuclear deterrent will rest with confidence in the competency of the people who must make the scientific and technical judgments related to the safety and reliability of U.S. nuclear weapons (U.S. Department of Energy, 1995).

This need to maintain competence is used as the main justification for the extensive scientific research program proposed under Stockpile Stewardship.

Stockpile Stewardship, then, is partly an effort to repair the discourse of credibility surrounding nuclear weapons. Nuclear testing is posed as a critical *but not irreplaceable* element of weapons knowledge. This subtle shift turned the end of testing into a rhetorical resource for the argument that the nuclear weapons complex *could* be repaired, but only with the investment of considerable resources in the weapons laboratories. This laid the groundwork for the major institutional repair to follow.

Material Repair

In terms of the material form of the weapons stockpile, Stockpile Stewardship is a clear example of repair as maintenance. While it transforms weapons knowledge and institutions, it aims to repair stockpile weapons only to the extent necessary to maintain them in their current state. This maintenance effort has several elements. A stockpile surveillance program pulls weapons from the active stockpile to perform a wide array of tests on them to determine their current physical condition. The performance of the stockpile as a whole, including any possible impact of aging, is assessed by an annual certification process, culminating in certification letters sent to the Department of Energy by the laboratory directors, and a memorandum to the President. The more active element of stockpile maintenance is the life extension process. This is essentially a reduced version of the weapons production cycle: designers and engineers identify which weapon components need to be refurbished or replaced, and then work with the remaining production plants to facilitate the remanufacturing process and certify the refurbished systems (U.S. General Accounting Office, 2009: 8-10).

What is striking here is the level of effort devoted to maintaining a set of technological artifacts in an essentially static state. Maintenance is a conservative form of repair, but it can often involve a great deal of institutional effort and the engagement of many communities of practice.

Institutional Repair

The main focus of transformative repair under Stockpile Stewardship has been the experimental cycle – in particular, the role in this cycle of weapons design codes, the

simulation tools used to model weapon performance. While code development had been a key aspect of the experimental cycle in the Cold War, testing was perceived as the final arbiter of confidence in the stockpile. The testing process was organized to be an integrated validation of weapons expertise, codes, and the functioning of particular weapons systems. Under Stockpile Stewardship, codes themselves were to take on this central integrating role, to 'fill the void, to the extent possible, left by the termination of nuclear testing.' Simulations would now be 'the principal way of evaluating the safety of nuclear assemblies and the only way of estimating full system performance' (U.S. Department of Energy, 1995).

The Stockpile Stewardship and Management Program made the case that major improvements in physics understanding and computing capacity would be needed if simulation were to take on this new role. This led to the creation of a massive capability-building program, the Accelerated Strategic Computing Initiative. This program and its successors have devoted large amounts of money to the development of faster and more sophisticated computers and new weapons codes that can make effective use of them, as well as a number of large, expensive experimental facilities aimed at understanding the fundamental physics of nuclear detonation.

The transformation in the experimental cycle has been profound. With codes, rather than tests, as the integrating element, patterns of collective work have changed dramatically. Weapons work is now organized in a much more deliberate way, around numerous small milestones on the way to incrementally improving weapons codes. As one code developer explained,

When we were doing testing, there were deadlines you had to meet - designers, engineers, manufacturers, experimentalists had to resolve things. Testing was a big deal, millions of dollars involved, riggers, diagnosticians, engineers, etc., so you couldn't miss deadlines – so people took the trouble to overcome distances. They tried to replace test deadlines with milestones, but then the milestones would slip, and people stopped paying attention to them. Without testing to hold them together, those collaborations have fallen apart.

As a result, weapons expertise is a less tightly integrated body of knowledge, and specialized sub-fields have taken on more independent roles.

Many weapons scientists who made their careers during the testing era, like the code developer quoted above, have experienced these changes purely as a breakdown in accepted ways of constructing weapons knowledge. But they are arguably part of the institutional transformation envisioned by Stockpile Stewardship: the disaggregation of expert communities made it possible to reorganize weapons work and knowledge around a new set of facilities, capabilities, and programs. The undercurrent of dissatisfaction with Stockpile Stewardship among weapons scientists – discussed in detail in the following section – is part of what marks this as truly transformative institutional repair.

Summary

Stockpile Stewardship takes a minimalist, maintenance approach when it comes to the technology in the nuclear stockpile. But it is built around the idea that simply maintaining things at the material level requires a thorough and costly transformation at the level of practices and institutions. In order to position these changes as both necessary

and sufficient to maintain a credible nuclear deterrent, weapons laboratory managers developed a discursive framework that deployed elements of the existing capability-based deterrence argument, with its focus on expertise, and joined them to a new vision of technical practice enabled by advances in modeling and simulation technology. As we will explore below, however, this vision was very much the product of a group of managers whose main interest was sustaining technical work and funding for the weapons laboratories. It was not necessarily shared by weapons scientists, who continued to resist the idea that their credibility could be maintained outside of the context of design work.

Repairing Credibility: The Reliable Replacement Warhead

RRW gained traction within the weapons community through the 1990s and the early 2000s because its proponents linked it to an increasingly well-defined set of concerns about Stockpile Stewardship. The idea of Stockpile Stewardship, and particularly its focus on computing and simulation had never been particularly popular among weapon scientists, as Sig Hecker described in our interview:

> The reaction to [the Accelerated Strategic Computing Initiative] in the design community was extremely negative. The hardcore designers wanted their own computing to solve their own problems. They thought ramping up capabilities was just building capability for the sake of building capability.

The worries of the technical community focus on the central role that weapon design codes are supposed to play under Stockpile Stewardship. These concerns fall into

two areas: 1) the relationship between codes and expert judgment, and 2) the relationship between codes and Cold War weapons.

Skepticism about the computing elements of Stockpile Stewardship is partly motivated by a perception, encouraged by the Department of Energy, that improving codes is a direct substitute for testing in maintaining weapons expertise. Many designers feel that codes should not be used to predict weapon performance without a link to expert judgment in the context of testing. The last generation of designers that had built their careers in the testing era was very strongly opposed to ending testing for this reason, and because they thought it would be impossible to train new generations of designers without testing (Mackenzie and Spinardi, 1995; McNamara, 2001: 236-273).

Weapons scientists with test-era experience are now willing to grant that 'codes are getting better' and 'ASCI codes are really powerful,' in some cases improving on legacy codes in their ability to calculate past nuclear test results. However, they still express concern that their younger colleagues might misuse codes, not having had the experience of test results demonstrating shortcomings in their code calculations: 'the younger folks haven't experienced enough to develop a sense of humility. They trust codes much more than they should.'

This message seems to have been well drilled into the younger designers. The ones we interviewed all expressed some degree of concern about relying on codes alone to understand weapons. Some put this in terms of disruption of the scientific method:

> [During the Cold War] they were in a healthy scientific and manufacturing environment, combining scientific principles with engineering testing. Now we are only 'one armed,' working only with scientific principles. By design, it's not a

complete environment to do a credible job.

Still, this designer expressed cautious optimism about improvements in weapons knowledge:

> If you put me in a time tunnel [back to the testing era] I think I can do a better job than those back then. I carry a lot of fundamental scientific ideas, but I need more opportunity to figure out how to apply that, I could be more well-rounded.

Another concern about Stockpile Stewardship focuses on the relationship between codes and Cold War weapons. These weapons were very sophisticated designs aimed at maximizing nuclear yield while minimizing the weight of warheads. As a result, a code developer argued,

> Stockpile Stewardship can't succeed with the existing stockpile because it's too close to the limits, we pushed everything down to the limits … it didn't matter how close to the edge we got, because we could replace weapons if they weren't working properly.

The idea here is that the tight performance margins of designs in the current stockpile leave little room to accommodate the effects of aging, or uncertainty about the impact of aging on performance.

Under Stockpile Stewardship, refurbishment of weapons is supposed to address aging issues, but on this point weapons scientists are also skeptical. The problems posed by aging weapons are sometimes discussed using an automotive analogy. One of our interviewees explained it as follows:

It's like you have a Chrysler coupe from 1982. It has an aluminum bumper, and that bumper accounts for 95% of its safety. The bumper was made of a certain alloy, by Alcoa, but Alcoa merged with another company and they no longer make it. There is a startup in California that makes the same alloy, but the trace metal composition is not the same. And, also, you have to meet modern safety standards.[10]

The sense is that changes made to accommodate these issues might accumulate over time. At some point, a weapon could become dissimilar enough from its tested version that the test record might no longer justify confidence in its performance.[11]

The technical arguments for the proposed RRW program were articulated at a more official level in *Sustaining the Nuclear Enterprise – A New Approach* (O'Brien et al., 2005), a joint report signed by weapons program managers at Livermore, Los Alamos, and Sandia National Laboratories. This report restates many of the arguments we heard from within the design community:

Should a future technical issue emerge that can only be resolved by a fundamental design change, the current application of [Stockpile Stewardship] neither preserves the competencies nor transfers the knowledge needed to design, develop, and manufacture replacement warheads of significantly different design (O'Brien et al., 2005: 5).

It reiterates the argument about margins and uncertainties, and discusses the concern about accumulated changes from aging and LEPs:

As we project forward, the current application of [Stockpile Stewardship] looks increasingly unsustainable. Current plans foresee the challenging tasks of

maintaining and refurbishing nuclear warheads produced in the 1980s until about 2040. As these warheads continue to age and are refurbished, an accumulation of small changes could lead to increased risk or increased uncertainty in warhead certification … this is a risky path (O'Brien et al., 2005:4).

The document goes on to articulate a case for building replacement weapons with higher performance margins.

Although RRW has more recently been pitched as a logical successor to Stockpile Stewardship, it actually originated during the same time period as Stockpile Stewardship, in the early 1990s. The idea of updating stockpile technology itself to meet the needs of long-term stewardship had been discussed widely across the weapons laboratories since at least the time of the test moratorium, and possibly as early as the 1980s. (Masco, 2006: 87; Kidder, 1997). It was not until design and testing stopped in the early 1990s, however, that these ideas began to coalesce around the problem of designing a weapon without testing that would be optimized for long-term stockpile storage. In 1994, a working group of Los Alamos designers began meeting to develop concepts for a 'robust bomb,' with 'robust' in this case indicating optimized for long-term stockpile storage. The RRW moniker was first attached to this concept, with the acronym standing for 'Robust Replacement Warhead.' The first word was later changed to 'reliable' to avoid confusion with the Robust Nuclear Earth Penetrator, a concept that had aroused considerable Congressional opposition.

The idea of developing new weapons for long-term stockpile use without testing was essentially the technical community's solution to the stockpile stewardship problem. At the time, however, it was viewed by laboratory and DOE management as not

politically viable. In our interview, Hecker explained that 'the political environment didn't make it possible to pursue RRW … people thought the world had changed, that we didn't need nuclear weapons anymore.'

Early support for RRW outside the weapons laboratories came mainly from within the Navy and the Department of Energy. One key supporter of RRW was Admiral G. Peter Nanos, a physicist responsible for the development of submarine-based strategic missile systems, who served a brief and turbulent term as Los Alamos Laboratory Director from 2003-2005. With Nanos' support, the RRW concept was carried to higher levels in the Department of Defense. At the same time, the concept was gaining traction within the Department of Energy, where it was incorporated into the 'Complex 2030' plan to revitalize the weapons production complex.

In 2003, RRW drew the attention of Representative David Hobson, chair of the House subcommittee responsible for Department of Energy appropriations. Hobson, an arms control advocate, apparently supported RRW primarily as a strategy for actively redirecting funding away from the Robust Nuclear Earth Penetrator and other weapons initiatives he saw as undermining nonproliferation. In 2005, Hobson maneuvered to transfer funding from these programs to RRW (Medalia, 2007). Hobson's politically pragmatic reasons for supporting RRW made him a problematic ally, however – a fact which would play a role in the demise of RRW funding in negotiations leading up to the 2008 budget.[12]

Discursive Repair

Sustaining the Enterprise presents a very different view of credibility than was described in *The Stockpile Stewardship and Management Program*. The argument for Stockpile Stewardship relied heavily on the concept of capability-based deterrence – the notion that the competence of weapons scientists was the key to successful nuclear deterrence. Its main concern was how to maintain this competence in the absence of testing. An analysis of concept frequencies in *The Stockpile Stewardship and Management Program* bears this out (Table 1). 'Capability' is the fifth most frequent concept in this document, while 'nuclear testing' is the third most frequent concept. By contrast, neither term appears among the ten most frequent concepts in *Sustaining the Enterprise.* Instead, this document gives much more emphasis to design work (the second most frequent concept) and also mentions Stockpile Stewardship quite frequently. This reflects its strategic use of Stockpile Stewardship as a motivator for RRW.

Table 1. Most Frequent Concepts Comparison between Key Stockpile Stewardship and RRW Documents[13]

The Stockpile Stewardship and Management Program (1995)		*Sustaining the Enterprise* (2005)	
Concept	**Frequency**	**Concept**	**Frequency**
Nuclear Weapon	156	Nuclear Weapon	116
Stockpile	101	Design	51
Nuclear Testing	64	Stockpile	51
Safety	61	Enterprise	40
Capability	56	Future	30
New	52	Security	30
Production	50	Stockpile Stewardship	29
Need	44	Should	24
Provide	40	Change	22
Facility	38	Cost	22

Where *The Stockpile Stewardship and Management Program* tied credibility almost entirely to the abstract technical knowledge of weapons scientists, *Sustaining the Enterprise* focuses on the role of the physical design of weapons and the composition of the stockpile in maintaining credibility:

> Warhead reliability should be strengthened to assure that, even with reduced stockpile numbers and with a receding test history, confidence in the U.S. nuclear deterrent remains high. Given the existing no-testing environment, high reliability and confidence can best be achieved by designing and fielding warheads that have larger performance margins. These margins must be sufficient to accommodate known and quantified uncertainties. In addition, to hedge against unknown failure modes, the stockpile should retain sufficient diversity to assure that no single problem dramatically weakens the entire stockpile (O'Brien et al., 2005: 7).

The theory of credibility first articulated as 'capability-based deterrence,' and elaborated in support of Stockpile Stewardship, treated weapons knowledge as a kind of generic expertise that existed independently of the material configuration of the stockpile itself. RRW, by contrast, articulates an explicit connection between the epistemological and the material, in which margins and uncertainties play the key mediating role. As long as margins are higher than uncertainties, its proponents argue, weapons knowledge remains relevant to the physical reality of nuclear weapons, and the ability of weapons scientists to speak credibly about the functionality of the stockpile is maintained.

Material Repair

As we have seen, proponents of RRW argue that a material transformation of stockpile weapons – in the form of replacement warheads – is the best way to maintain the credibility of weapons knowledge. In 2005, an early-phase RRW design competition was held between Los Alamos and Livermore design teams. At this point, a Project Officers Group was formed to oversee the process, and specific design requirements were developed. While the specific requirements remain classified, minutes of a June 2005 meeting include a formal list of priorities for RRW:

- Safety

- Security/Use Control

- Cost

- Certifiability

- Manufacturability

- Reliability

- Survivability

- Yield

- Longevity (ITT Industries, 2005: E-10)

As this list suggests, once redesign of weapons was on the table, other interested groups in the military and Department of Energy began introducing their own priorities into the design process, in particular placing safety and security at the top of the list, and adding militarily relevant characteristics like survivability and yield.

Much to the chagrin of the Los Alamos designers, who saw themselves as the originators and champions of RRW, the Livermore design was declared the winner of the

competition in March 2007. The Department of Energy saw the Livermore design as more conservative because the design team had based it on a specific weapon system that had been tested in the 1980s and rejected for being 'overweight and heavy.' The Los Alamos design, by contrast, was based on many different nuclear tests, but was not closely linked to a specific weapon that had been tested (Kinitsch, 2007).

So, ironically, despite the transformational goals of RRW (as seen by Los Alamos designers) the design that was seen as least innovative, and materially closest to a specific technological artifact from the past, won out. This again suggests some of the subtleties and difficulties of successful repair, in which transformational goals are often balanced against a preference for conservatism and preservation of past modes of practice.

Institutional Repair

In documents like *Sustaining the Enterprise*, RRW is positioned as enabling a comprehensive institutional reorganization of the nuclear weapons complex:

> To meet requirements, the nuclear weapons enterprise of the future should be smaller, responsive to change, safe and secure, and able to design, produce, certify, and maintain the nuclear weapons needed for deterrence. It must be affordable. Changes in the design of stockpile weapons will enable changes in the enterprise that develops, produces, and certifies them. This means changes in both the production complex and the national laboratories (O'Brien et al,. 2005: 8).

From the perspective of the design community, however, the principal institutional repair associated with RRW is the partial restoration of the weapon development cycle. During the course of the design competition, weapons scientists fully exercised elements of the

weapon development process for the first time since the end of the Cold War. The designers and engineers we talked to felt this was an extremely useful learning experience, and helped reestablish some of the relationships that had dropped away in the Stockpile Stewardship era. In particular, it enabled younger designers to better appreciate the practical complexities of nuclear weapon design. With the end of the RRW program, however, it is unclear whether those new relationships will be maintained.

Summary

Unlike Stockpile Stewardship, RRW was conceived of squarely within the weapons science community, and came to reflect that community's preferred approach to repairing its credibility in the absence of nuclear testing. RRW was initially designed to solve technical problems this community was directly concerned with, particularly the challenge of ensuring that uncertainties about weapons performance would not exceed the performance margins of stockpile weapons. Not surprisingly, given that it was developed by designers, RRW posed design solutions to this problem.

While laboratory managers may have felt that the abstract expertise of weapons designers backed up institutional claims to credibility, designers are more conscious that their expertise is closely tied to a concrete set of material resources – namely, the specific collection of weapons designs in the nuclear stockpile. As a result, they see material repair as a necessary accompaniment to institutional repair, or even the primary driver of institutional repair, where the originators of Stockpile Stewardship saw the two as separable.

Discursively, it still fell to high-level managers within the weapons laboratories to justify RRW on grounds that would be politically acceptable. To do this, they rearticulated the technical community's arguments for RRW in a way that did not undermine the foundations of Stockpile Stewardship, while attaching RRW to an array of politically appealing issues, such as cost cutting and reduction of nuclear forces.

Conclusions

Sociotechnical repair, particularly when it plays out in the context of a multifaceted material and institutional environment like the nuclear weapons complex, is a dynamic and complex process. One reason for this is the fact that institutions are not unitary entities: at some level, institutions have 'interests,' but different groups of actors within an institution may have different ideas about what those interests are. When an institution is undergoing major changes, as in the nuclear weapons complex following the Cold War, efforts at institutional repair may serve to reveal hidden differences between groups.

Stockpile Stewardship, for example, was worked out by a small group of influential actors within laboratory and DOE management. These actors conceived of Stockpile Stewardship as having something to offer the technical community, in the form of experimental and computing resources needed to fill in long-standing gaps in knowledge of weapons physics. The technical community saw these resources as possibly necessary, but not sufficient to maintain their ability to speak credibly about weapons performance. However, they realized that their preferred alternatives – continuing with

testing, or designing replacement weapons that could be certified without testing – were not politically viable.

As Stockpile Stewardship was being implemented, the technical community continued to work on the replacement weapon option, which eventually became a consensus approach to resolving the technical community's concerns about Stockpile Stewardship, at least at Los Alamos. By exploiting key allies in the military and the DOE, the technical community was able to link RRW to a range of interests surrounding nuclear weapons, until it came (for a time) to be seen as a necessary next step by managers, DOE officials, and key members of Congress.[14]

As these examples show, building momentum around repair strategies in the nuclear weapons complex was a process in which powerful groups developed plans, sought to enroll allies within and outside the institution, made strategic decisions to go along with plans that didn't fully serve their interests, and retreated from certain goals in order to regroup and push their interests at a better time. We would expect to see similar dynamics of interests and power in other complex sociotechnical systems undergoing transformational repair.

An important point of comparison between Stockpile Stewardship and RRW is the different balances they strike between the material and institutional aspects of repair. During the Cold War, weapons expertise had been underwritten by an intricate, tightly coupled network of material and institutional resources that were organized around testing and production of nuclear weapons. When these activities went away, the existing relationship between the material and the institutional broke down, and different ways of repairing it were proposed.

Stockpile Stewardship accepted a very conservative, maintenance approach to the stockpile itself, in part due to political sensitivities. However, its proponents argued that maintaining the stockpile in this way could only be accomplished with a massive investment in institutional transformation, to build up the new forms of scientific knowledge needed to certify the aging stockpile without testing. They made sense of this trade-off through a discursive repair strategy that positioned weapons knowledge as an abstract entity that could be developed independently of the material form of nuclear weapons. By doing so, they were able to argue that the credibility of weapons knowledge could be sustained through institutional repair alone.

The proponents of RRW challenge this separation between weapons knowledge and the materiality of nuclear weapons. Instead, they argue that the two are inextricably linked: uncertainties in weapons knowledge must be accommodated by performance margins built into the weapons themselves. Maintaining this relationship, they claim, is crucial to sustaining the credibility of the nuclear weapons enterprise. They use this discursive strategy to back up their claim that material as well as institutional transformation is needed in order to effectively repair the nuclear weapons complex.

The shifting relationship between material, institutional, and discursive elements of repair in Stockpile Stewardship and RRW highlights the robustly sociotechnical nature of both repair and credibility. In neither case were material or institutional repairs proposed in isolation from one another; instead, there was a dynamic relationship between the two.

In Stockpile Stewardship, fundamental changes in the technological basis of weapons knowledge were both enabled by, and served to sustain, changes in professional

roles and social interactions. In particular, the shift of focus toward modeling and simulation technologies enabled a more dispersed structure of interactions among weapons scientists. This, in turn, made it possible to articulate credibility in terms of a more abstract view of weapons knowledge that divorced it from the material condition of the stockpile. However, this switch to a more abstract basis of credibility was itself driven by the introduction of new material artifacts: computer systems, instruments, and experimental facilities. This shifted the relationship between the social and the technical, but they remained part of an integrated sociotechnical system.

RRW, by contrast, represents the view that technical credibility arises at the intersection of weapons technology and design expertise, which is represented by the relationship between margins and uncertainties. Its proponents argue that repair of the credibility of weapons knowledge can best be accomplished within the context of designers' engagement with the materiality of weapons, even in the absence of testing. However, RRW proposes a new paradigm for weapons design that does not require the large-scale sociotechnical systems of the Cold War nuclear weapons complex. This leads to a view of credibility that incorporates the new sociotechnical arrangements created by Stockpile Stewardship, while making the case for the continued relevance of design activities that will impact the material form of nuclear weapons.

These examples suggest that credibility can be understood not only in terms of personal trust within technical communities, or formal mechanisms and demonstrations in a public context, but also in terms of the dynamics of sociotechnical systems. Technical communities and other institutional actors establish credibility by discursively mobilize the sociotechnical resources they control. In doing so, they in turn make the case

for the credibility and relevance of the sociotechnical system as a whole, and underwrite the legitimacy of their claims of control over particular sets of practices. During the Cold War, the weapons design laboratories positioned themselves as the orchestrators of the entire web of nuclear weapons activities, and gained legitimacy to speak for the entire complex by virtue of their claims of expert authority about nuclear weapons matters. This authority was backed up by the continual production and testing of new nuclear weapon designs.

Drawing on their existing ability to speak for the weapons complex as a whole, the weapons laboratories were able to articulate, and gain acceptance for, a post-Cold War narrative which continued to position their expertise as a central element of nuclear deterrence. This narrative has played an important role in maintaining the political legitimacy of the idea that maintaining a basic nuclear deterrent without testing is both possible and desirable.

At the end of the Cold War, the weapons community at first resisted change by adopting a conservative argument about the need to preserve tacit knowledge. Following this line of argument, MacKenzie and Spinardi (1995) argued that tacit knowledge was a key element of weapons designers' ability to speak credibly about the reliability of weapons. They speculated that loss of the Cold War context of nuclear weapons knowledge could erode the "cognitive authority" of weapons designers, possibly resulting in a serious crisis of credibility for nuclear weapons expertise.

Our study of the Stockpile Stewardship and RRW programs shows that the weapons community's descriptions of its own knowledge continued to evolve after the end of the Cold War, particularly when it became clear that nuclear testing would not be

returning soon. Facing a threat to its very existence, the community began to articulate visions of how its knowledge could remain credible even in the absence of testing and weapons production. In some cases, these visions conflict with the tacit knowledge perspective advocated by MacKenzie and Spinardi and the scientists they interviewed. In particular, Stockpile Stewardship and RRW cast tacit knowledge as a flexible and adaptable resource that can be successfully maintained and transformed within new sociotechnical contexts without losing its credibility.

This is not to say that MacKenzie and Spinardi, or their informants, were wrong about the essential nature of nuclear weapons knowledge. It is simply to say that the conservative tacit knowledge argument they advanced has proven not to be essential to the continued credibility of weapons knowledge. The flexibility the weapons community has displayed in describing its knowledge suggests that it is imperative that we pay close attention to the discursive work being done when a community makes claims about the essential nature of its knowledge. Claims about the fragility, flexibility, intangibility, context dependence, abstraction, rigidity, generality, or uniqueness of knowledge are often closely tied to a group's political and institutional interests, regardless of whether those claims match up with sociological or philosophical theories of knowledge.

The study of repair, among other things, provides a window into the complex relationship between knowledge, credibility, and institutional change. In particular, it shows that regimes of knowledge and credibility are not static, but are dynamically maintained through ongoing processes of repair and revision. It is possible that the nuclear weapons complex could face an irreparable crisis of credibility in the future that could lead to something like the 'uninvention' proposed by MacKenzie and Spinardi. But

in the case of Stockpile Stewardship and RRW, we observe that weapons knowledge has

been continually reinvented and repositioned within new contexts of credibility. At this

point in time, weapons scientists continue to exercise their cognitive authority, national

leaders are convinced of their credibility, and the basic conditions required for

maintaining a credible nuclear deterrent continue to be satisfied.

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Notes

[1] Interviews were conducted between April 2006 and July 2007. This paper represents the views of the authors. The Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; therefore, the Laboratory as an institution does not endorse the viewpoint of a publication or guarantee its technical correctness.

[2] See especially Bijker, Hughes, and Pinch (1987); Latour (1996); Vaughan (1996); Perrow (1999); Law (2002); Drori et al. (2003).

[3] We use the term 'sociotechnical' to emphasize the social and material character of complex systems, where diverse social and technological elements contribute to a system of production. See Bijker, Hughes, and Pinch (1987); Bijker and Law (1992); Bijker (1995); Latour (1996); Law (2002). Although we frequently list categories of analysis such as institutions or technologies as separate terms, this is a matter of methodological and descriptive convenience; our overall analysis intends to show the links between these varied factors and how they contribute (or not) to the credibility of the nuclear weapons complex.

[4] Similarly, institutional breakdowns in the New Orleans Police Department were well understood before the storm, but efforts to repair them were limited, contributing to the organizational collapse of the department following the storm (Sims, 2007b, 2009).

[6] Or, as one weapons designer put it, a credible deterrent is one that can 'scare small children' (quoted in Leibovich, 1998).

[7] The term 'design' carries a unique set of meanings within the nuclear weapons community. 'Designers' are responsible for the material layout of a weapon and for

predicting its performance from a physics standpoint. The detailed design work necessary to translate this overall configuration into a system that can be built and fitted into a delivery vehicle is the responsibility of engineers who are not considered 'designers.'

[8] Previous studies of the nuclear weapons complex have often focused on the nuclear weapons 'design and test' activity cycle as the central integrating process in the nuclear weapons complex during the Cold War. However, we have found that the nuclear weapons community has begun to pay more attention to the impact of losing development and manufacturing activities.

[9] Hecker attributes the origins of the idea to Los Alamos weapons program managers John Immele and Rich Wagner.

[10] This analogy both serves to explain weapons issues in non-technical terms, and articulates weapons scientists' view of weapons as mundane technology, irrespective of their global political import.

[11] See MacKenzie (1989) and Pinch (1993) for discussion of the critical role similarity judgments play in testing in general.

[12] It is also noteworthy that, despite support for RRW at relatively high levels within the departments of defense and energy, it never attracted enthusiastic support from cabinet-level officials in the Bush administration. This was possibly related to the way Hobson and his colleagues had used RRW to maneuver funding away from nuclear weapons initiatives favored by the administration.

[13] These frequency lists were generated using AutoMap software. A standard set of minor words (and, the, etc.) were omitted, and stemming was applied. A concept thesaurus was

developed and applied to group similar terms into common concepts (i.e. 'weapon systems' and 'nuclear warheads' map to the 'nuclear weapons' concept).

[14] It is worth noting that less powerful elements of the nuclear weapons complex, such as the production plants, were never able to successfully mobilize resources or gain allies to repair their practices and protect their interests, and suffered massive cutbacks as a result.