Maintaining the Atom

U.S. Nuclear Power Plant Life and the
80-Year Maintenance Regulation Regime

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ABSTRACT

Large, ever more complex, technological systems surround us and provide products and services that both construct and define much of what we consider as modern society. Our societal bargain is the trade-off between the benefits of our technologies and our constant vigilance over the safe workings and the occasional failures of these often hazardous sociotechnical systems during their operating life. Failure of a system's infrastructure, whether a complex subsystem or a single component, can cause planes to crash, oil rigs to burn, or the release of radioactivity from a nuclear power plant. To prevent catastrophes, much depends not only on skilled and safe operations, but upon the effective maintenance of these systems.

Using the commercial nuclear power industry, of the United States, as a case study, this dissertation examines how nuclear power plant maintenance functions to ensure the plants are reliable and can safely operate for, potentially, eighty years; the current, government regulation defined limit, of their functional life. This study explores the history of U.S. nuclear maintenance regulatory policy from its early Cold War political precursors, the effect of the 1979 Three Mile Island reactor melt-down accident, through its long development, and finally its implementation by nuclear power licensees as formal maintenance programs. By investigating the maintenance of nuclear power

plants this research also intends to expand the conceptual framework of large-technological-system (LTS) theory, in general, by adding a recognizable, and practically achievable, end-of-life (EOL) phase to the heuristic structure. The dissertation argues that maintenance is a knowledge producing technology that not only keeps a sociotechnical system operating through comprehension, but can be a surveillance instrument to make system end-of-life legible; that is both visible and understandable. With a discernible and legible view of system end-of-life, operators, policy makers, and the public can make more informed decisions concerning a system's safety and its continued usefulness in society.

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GENERAL AUDIENCE ABSTRACT

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To prevent catastrophes, much depends not only on skilled and safe operations, but upon the effective maintenance of these systems.

Using the commercial nuclear power industry, of the United States, as a case study, this dissertation examines how nuclear power plant maintenance functions to ensure the plants are reliable and can safely operate for, potentially, eighty years; the current, government regulation defined limit, of their functional life. This study explores the history of U.S. nuclear maintenance regulatory policy from its early Cold War political precursors, the effect of the 1979 Three Mile Island reactor melt-down accident, through its long development, and finally its implementation by nuclear power licensees

as formal maintenance programs.   By investigating the maintenance of nuclear power plants this research also intends to develop a method to determine when a nuclear power plant, or other large technological system, is approaching or has reached the end of its reliable and safe operational life. The dissertation presents maintenance as a technology of knowledge that not only keeps a system operating through understanding of its components, but can be a general surveillance instrument to make system end-of-life legible. With a discernible and understandable view of end-of-life, operators, policy makers, and the public can make more informed decisions concerning a system's safety and its continued usefulness to society.

富子さんへ

To Tomiko-san

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Truly successful and meaningful endeavors are not the creation of one person. This work is not an exception. I was extremely fortunate to have an outstanding group of people who shared not only their expertise and experience, but provided me unfailing support from the conceptual beginning of this project to what you are now reading.

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Dr. Vinsel introduced to me his scholarly expertise on maintenance. His thoughts reshaped my own views on maintenance and added a broader and more enhanced dimension to my study of nuclear systems maintenance. I could not have asked for a better committee.

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Also, I wish to thank the NRC's historian, Dr. Thomas Wellock. I was fortunate to have him there at the conceptual beginning of this project. He encouraged me to pursue an examination of the politics and the practicalities of U.S. nuclear power plant maintenance. As the resident expert of NRC history Dr Wellock recognized that study

of the formalization of nuclear maintenance would be a useful and interesting pursuit since it has remained largely unexamined.

Although this work focused exclusively on the maintenance of commercial nuclear power plants in the United States, I also owe considerable thanks to Kenji Tateiwa of the Tokyo Electric Power Company. He shaped my thinking by providing me a keen comparative perspective of how nuclear systems are professionally managed in Japan. Furthermore, his own professional technical briefs of the recovery operations at Fukushima Daiichi, reemphasized to me the extreme consequences of large technological system failure.

I also cannot thank my anonymous interviewees enough for the time they voluntarily devoted to my research. They hailed from inside and outside the commercial nuclear industry and from the U.S. Nuclear Regulatory Commission. They provided me the practical real-world experience and insight of working with and within the commercial nuclear power industry. The interviewees were both professionally and personally candid and especially enthusiastic about relating their experiences. They are an impressive group and represented the nuclear community extraordinarily well with their technical and policy expertise and experience. They are true system professionals.

Finally, I most ardently wish to thank my best friend, true supporter, and wife, Tomiko Miller. She encouraged and pushed me to succeed and was always quick to prod me whenever I waivered. Tomiko also contributed invaluable technical assistance by helping me capture thousands of pages of documents from the NRC's historical

archives. I can never thank her enough for her patience and support and I dedicate this dissertation to her.

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Introduction

Topic and Significance of Study

If you were traveling through the U.S. state of Illinois you would have a good chance of seeing, perhaps in the distance, a nuclear power plant. Illinois has six plants that operate a total of eleven nuclear reactors; the most reactors of any state in America.[1] How do we know if those plants are operating safely and not in need of repair? Over the life span of a plant, and among its thousands upon thousands of components, what should we repair? When should we repair it and how do we repair it? Most critically, how can we prevent it from requiring repair in the first place? If a nuclear power plant's safe and reliable functioning is of vital concern (and its failure potentially disastrous) then we must assure ourselves that, as the plant ages, we fully comprehend the condition and health of the entire plant system to include both its nuclear and non-nuclear components.

Society's large, and often hazardous, technological systems surround us and provide all manner of services that construct and define much of what we consider as modern society. Our societal bargain is the tradeoff between the benefits of our

[1] U.S. Energy Information Administration 2019b.

technologies and our constant vigilance over the safe workings (acceptable risks) and occasional failures of these hazardous systems. Failure of a system's infrastructure, whether a complex subsystem or a single component, can cause planes to crash, trains to derail, ships to sink, cities to blackout, oil rigs to burn, or cause the uncontrolled release of radioactivity from a nuclear power plant. Intertwined with proper system operations, effective maintenance is critical to ensuring that the infrastructures of the 59 nuclear power plants, with 97 reactors, in the United States (as of 12 September 2019) are functioning properly and safely, as designed, over their engineered life span.[2]

The operating age of these reactors spans from nearly 50 years for the Nine Mile Point Nuclear Station, Unit 1, in New York state, that began producing commercial power in December 1969,[3] to less than three years for Tennessee's Watts Bar Unit 2 that started full operation in October 2016 after a two decade construction pause.[4] If the current U.S. nuclear regulatory and maintenance regime continues as envisioned, then Nine Mile Point Unit 1 reactor could conceivably operate until 2049 (that is, for 80 years) and Watts Bar Unit 2 may generate electricity to within four years of the 22nd century (the year 2096).[5] Doubling the safe life span of nuclear power plants, originally planned to have a 40 year operating life, depends much upon the unfailing maintenance of these incredibly complex systems. How are the systems' regulators and maintainers implementing this 80 year nuclear power plant maintenance regime? How will they

[2] U.S. Nuclear Regulatory Commission 2019b. As of 20 September 2019, Exelon Corporation shutdown Three Mile Island Unit 1 for decommissioning. It could no longer be economically operated without State Government subsidies. This reduced the number of plants to 58 and reactors to 96 (Exelon 2019)..
[3] Rolph 1979.
[4] Tennessee Valley Authority 2019.
[5] U.S. Nuclear Regulatory Commission 2006.

know the what, when and how of effective nuclear power plant infrastructure maintenance as a long term (or perhaps indefinite) proposition of society sustaining the life cycle of safe and reliable nuclear power systems? It is the life cycle of a regulatory rule governing maintenance that I will follow to help lead me toward answering these questions. I discovered that it was an intricate and interesting journey.

What maintenance?

> "I recognize that my personal view is we are coming to this emphasis on maintenance awfully late in the game…"
>
> - NRC Commissioner Lando W. Zech[6]

It was a long path to maintaining the atom. Twenty-nine years after the first privately owned and operated nuclear power plant, Unit 1 of the Dresden Nuclear Power Station, in Illinois, first went critical on 15 October 1959,[7] Victor Stello, the Nuclear Regulatory Commission's (NRC) Executive Director for Operations, briefed the NRC Commission on the NRC's *Interim Policy Statement on Maintenance* (SECY-87-314).[8] This in-work policy addressed nuclear power plant maintenance with a look toward increasing safety by ensuring licensees performed adequate maintenance. Commissioner Zech's candid and seemingly somewhat surprised response showed that maintenance was assumed by NRC senior leadership. Zech was a retired Vice Admiral and U.S. Naval nuclear officer so he recognized maintenance as a fundamental system activity and discovering

[6] Zech 07 January 1988.
[7] Rolph 1979.
[8] U.S. Nuclear Regulatory Commission 1987.

that commercial nuclear plants were not systematically maintained was probably quite shocking.

Three and a half years previously the NRC staff had developed a *Maintenance Program Plan*[9] that, as its name describes, recognized that nuclear power plant maintenance requires formal establishment and implementation and was something that the U.S. nuclear industry sorely lacked:

> "Despite expensive surveillance testing requirements, the NRC's rules and regulations provide no clear programmatic treatment of preventive maintenance."[10]

The March 1979 accident at Three Mile Island Unit 2 (TMI-2), near Harrisburg Pennsylvania, was the pivotal, and initiating event, that pushed the NRC down the path toward development and implementation of a program to ensure effective maintenance.

> "Ever since the Three Mile Island accident in 1979, it has been evident that faulty maintenance practice is a principal contributing factor to operating abnormalities."[11]

Even with a reactor core meltdown and its initiating event attributed to maintenance, it was several years before the NRC began to fundamentally change its view toward maintenance as something more than "work" to be down when something fails. As we will see later, this narrow maintenance mindset was evident in the investigative reports of the TMI-2 accident by both the NRC and the nuclear industry. That limited thinking had contributed to ending the life of the TMI-2 reactor just eighty-eighty days after it had

[9] U.S. Nuclear Regulatory Commission 1984b.
[10] U.S. Nuclear Regulatory Commission 1984b, 3.
[11] U.S. Nuclear Regulatory Commission 1984b, 3.

started commercial operations.[12] It is how the NRC and the nuclear industry expanded this restricted thinking and built regulatory and maintenance program tools for more effective understanding of nuclear power system life that is a focus of my research.

Research Questions, Science and Technology Studies (STS) Theory, and the Maintenance Rule

The fundamental regulatory tool governing commercial nuclear power plant maintenance in the United States is commonly referred to as the "maintenance rule." It was published by the United States Nuclear Regulatory Commission (NRC) on 10 July 1991 as 10 CFR 50.65, *Requirements for monitoring the effectiveness of maintenance at nuclear power plants.*[13] The NRC's maintenance rule is the overarching regulatory tool that guides U.S. nuclear power plant maintenance and shapes how maintenance and risks are assessed as nuclear plants proceed into their 60 and even 80 year life spans. My research follows the maintenance rule's life from its precursor historical events and regulatory activities, to its negotiated development, its implementation by power reactor licensees with NRC and industry guides, and finally through its current use and effects. Ultimately, the maintenance rule became the foundational element of the U.S. commercial nuclear power system maintenance regime and a key knowledge producing component for the understanding of system life. My dissertation examines the workings of this nuclear power plant maintenance regime. Its purpose is to answer

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[12] Walker 2004.
[13] U.S. Nuclear Regulatory Commission 1991.

the questions: How does the maintenance regime function to ensure nuclear power plants are reliable and can safely operate for, potentially, eighty years? Why, how and by whom was the maintenance regime constructed? Furthermore, can it function as an analytical tool to make legible the end-of-life of large technological systems to better inform the decisions of operators and policy makers?   This study looks at the history of the maintenance regime and argues that its original construct was shaped by the post World War II sociopolitical nuclear environment. It examines how that initial construct of maintenance practice was linked to the Three Mile Island Unit 2 accident in 1979. It goes on to show how the accident was the initiating event that served to force change of the maintenance regime through development and implementation of government regulation; the Maintenance Rule. Furthermore, I argue that maintenance is a *knowledge* technology that not only keeps a system safely and reliably operating through comprehension, but can be an instrument to recognize large sociotechnical system end-of-life.

Large Technological Systems (LTS) and End-of-Life (EOL)

Thomas Hughes described the development of a typical LTS in what he called a "pattern of evolution" that moves from invention, development and innovation to growth, competition and consolidation.[14] He did not mention end-of-life. He did appear to recognize a system's end-of-life phase with the cursory comment that, "countless

[14] Hughes 1987, 56..

technological systems have arrived at a stage of stasis and then entered a period of decline."[15] Hughes left us with a challenge: "Historians and sociologists of technology should also search for patterns and concepts applicable to these aspects of the history of technological systems."[16] By examining U.S. nuclear power systems, I intend to contribute to filling this gap with research that addresses the question of when does a large, complex, sociotechnical system reach the end of its safe operational life? How is this life span determined and who decides, especially if the system is hazardous and its failure will have disastrous consequences? Additionally, I want to show that technological end-of-life is not necessarily a distinct and obviously apparent state, but that it can be made legible. Technological systems do not typically die and wink out of existence to be replaced by the new. David Edgerton, in *The Shock of the Old*,[17] argues that a reexamined history of technology shows that societies continue to use and also re-use technologies long after their innovative shine has dimmed. He points out that, "The post-modern world has forty-year-old nuclear power stations as well as fifty-year old bombers."[18] Now, as of my writing in 2019, the U.S. has fifty-year-old nuclear power stations and fifty-seven-year-old B-52 nuclear bombers. Adding the end-of-life phase, with appropriate indicating methods, creates a more comprehensive LTS theory; a heuristic that could attend to providing an improved and safer system life-cycle construct. An awareness of system end-of-life can provide policy makers, regulators,

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[15] Hughes 1987, 80. Hughes gave credit to Richard Hirsh for the concept of stasis from an unpublished manuscript by Hirsh. Hirsh further developed the concept of stasis in his book, "Technology and Transformation in the American Electric Utility Industry" (Hirsh 1989).
[16] Hughes 1987, 80.
[17] Edgerton 2007.
[18] Edgerton 2007, Introduction. Kindle.

system architects and operators and maintainers, a better end-to-end view of sociotechnical systems. A system's decline would be legible and therefore subject to more effective management and control.

Description of the Dissertation

Chapter 1 provides a literature review and the theoretical concepts I am using to examine the maintenance and life of large-technological-systems with U.S. commercial nuclear power systems as the use case. Chapter 2 gives a historical perspective of the early (1950s) political and technical nuclear environment and argues that it adversely affected commercial nuclear plant operations and maintenance philosophies. Chapter 3 focuses on the Three Mile Island (TMI) accident to include its causes, aftermath, and numerous post-accident assessments. I will show how the TMI accident was the pivotal and initiating event that began a relook at nuclear power plant maintenance and development of the maintenance rule. Chapter 4 is my description of how the NRC, the nuclear power plant (NPP) licensees, and the U.S. nuclear power industry's policy organization, the Nuclear Management and Resources Council (NUMARC) (that later became the Nuclear Energy Institute (NEI)], implemented the maintenance rule. I examine how these organizations made it work administratively and, most critically, how they practically implemented the maintenance rule as a working standard with associated performance measurements and inspections. Chapter 5 looks at how the maintenance rule changed the nuts and bolts meaning of nuclear power plant maintenance and its fundamental tenants of reliability and safety. It describes how maintenance philosophy shifted from the mentality of fossil fuel power generators (power production is money) where the plants were typically run until they failed, to that of failure prevention and continual surveillance in the nuclear realm. I also describe my concept of maintenance as a knowledge producing technological system component and how it can be used to make legible system end-of-life via a model EOL system/component indicator.

Chapter 1
Literature Review and Methodology

Large Technological Systems (LTS)

Science and Technology Studies literature has provided several views of large technological systems spanning areas from the physical artifacts to a system's methods and policies of operations. These include: 1) system construction and development,[19] 2) system history,[20] 3) system operations,[21] and, often, 4) system failures.[22] There is theory on LTS origin and historical evolution. There are details of what it requires for an organization to operate as a large, and highly reliable, technological system.[23] There is also much STS literature documenting, in granular analysis, the failures of large sociotechnical systems, highly reliable or not.[24] The studies of failure have also led to extensive work, by STS researchers, on the political and technical responses to the often disastrous consequences of failed systems.[25] The failure analysis tends to focus

[19] Bijker, Hughes, and Pinch 1987; Hughes 1998; Rees 1994.
[20] Abbate 1999; Bugos 1996; Duncan 1990; Hirsh 1989; Hughes 1983; Mazuzan and Walker 1985; Schmid 2015.
[21] Perin 2005; K.H. Roberts 1990; Sagan 1993.
[22] Perrow 1999; Sagan 1993; Snook 2000; Vaughn 2003.
[23] Perin 1998; K.H. Roberts 1990.
[24] Perrow 1999; Sagan 1993; Snook 2000; Vaughn 2003.
[25] Knowles 2011; P. Roberts 2010; Schmid 2013.

on the direct operational failures of personnel (what they did or did not do) and procedures (what was required to be done or not to be done) that, more often than not, have upstream root causes located in the social, technical and political design of the system. This analysis places an emphasis on the functional aspects of a system's operations without typically identifying or focusing when in the system life cycle the events are occurring. Here is where an examination of system maintenance could help to illuminate the characteristics of a system as it approaches or enters end-of-life. Why maintenance? Because, like the human body, as a system ages it typically requires more upkeep to sustain its functionality where "things will move from a low-maintenance regime to a high-maintenance regime as they get older."[26] The level of upkeep or maintenance should be a good metric or indicator of a mature system's location in its life-cycle where increased maintenance activities generally have a correlation with age and quality of function.[27]

Maintenance, keeping the system's critical components in good working order and repairing then when they do fail, has not typically been the subject of extensive STS research. Perhaps STS researchers have considered the upkeep of the underlying fabric of large technological systems as mundane work. Generally, static slabs of concrete and steel (unless they compose a dam or skyscraper) and nuts, bolts, gears, and welds are not glamorous or considered to be in the realm of the technological sublime.[28] We may see documentaries about dam or building construction and be

[26] Edgerton 2007.
[27] Blanchard, Verma, and Peterson 1995.
[28] Nye 1994.

awed by their enormous scale and innovative construction methods, but once the concrete and steel are set in-place they often become infrastructure; subsumed and unnoticed in our sociotechnical landscape.[29] Perhaps they retain some of their impressiveness due to size, but rarely is the day-to-day infrastructure maintenance showcased unless it happens to be extremely hazardous and requires even more innovative technologies to perform. The physical actions of inspecting a weld or measuring water seepage is not extraordinarily interesting even if it's being performed in a nuclear reactor containment structure. As David Edgerton put it, "maintenance and repair are matters we would rather not think about. Mundane and infuriating, [they are] full of uncertainties."[30] So, we often consider it to be just work, but it is work that is as critical to minimize the risk of catastrophic failure as is proper operations. The failure of a mundane electrical relay or mechanical bearing in a nuclear power plant could potentially lead to loss of reactor cooling, causing reactor fuel core damage, and the uncontrolled release of radiation into the environment. Preventing or reducing the risk of radiation release is a primary focus of the NRC and, clearly, sustaining (maintaining) a functional system infrastructure is fundamental to that objective. With a focus on critical maintenance, there is some innovative STS research being done. Russell and Vinsel challenge the concept of innovation, that is typically viewed by modern societies as being coupled tightly with technological benefit and argue that we should realize that "technology is not innovation. Innovation is only a small piece of what happens with

[29] Busch 2011; A. Russell 2015; S.B. Star, Geoffrey C 2006.
[30] Edgerton 2007, Chap. 4, Kindle.

technology."[31] What happens with technology? It lives. It has a life and is used and depended upon by society for the long term. Preventing the failure of existing technological infrastructure is the required and expensive logistics tail. Effective maintenance is a critical component of this logistics support and, "for most...it is maintenance that matters more [than innovation]."[32] The work of maintenance keeps the infrastructure working. It is how we strive to safely live with our once innovative technologies. In other work, Russell emphasizes, with a combination of consternation and subtle humor, how our set-in-place technological infrastructures are typically considered uninteresting, unrecognized, and ultimately unseen in plain sight.[33] This view of infrastructure is what Susan Star described as "frequently mundane to the point of boredom, involving things such as plugs, standards and bureaucratic forms."[34] Russell argues that if we focus on technological innovation and consider infrastructure, as "nothing special"[35] it is at the expense of having uninformed policy decisions failing to "guarantee reliability, especially under conditions of duress"[36] of our critical infrastructures.

In his article, *Designing to the Test*, Vinsel closely examines technological performance standards, that address technical risks, and their regulation. He presents a three part analysis framework that assesses how regulators "*construct* and *enforce"* standards and how organizations "*internalize*" standards for effective and consistent

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[31] Russell and Vinsel 2016.
[32] Russell and Vinsel 2016.
[33] A. Russell 2015.
[34] S.L. Star 1999.
[35] A. Russell 2015.
[36] A. Russell 2015.

implementation.[37] This framework provides a useful view of infrastructure maintenance. It engages with the end-to-end mechanics of component pass/fail/tolerance criteria (standards) development, and the methodologies implemented and institutionalized for monitoring, inspecting and assessing the functioning of the components (maintenance). As we will see, the construction, enforcement and internalization of the performance-based Maintenance Rule was, in several respects, an interesting collaborative endeavor between the NRC and the nuclear industry.

Maintenance programs keep a system alive throughout its complex, use-centered life. This functional sustainment is comprised of "all actions necessary for retaining a system or product in, or restoring it to a desired operational state."[38] That state, according to the NRC's overarching maintenance regulatory policy or Maintenance Rule, is to "provide reasonable assurance that...structures, systems, and components...are capable of fulfilling their intended functions."[39] Within a nuclear power plant, the vast number of parts, their multiple interfaces, the next higher assemblies of systems, and all supporting infrastructures must be continually monitored, inspected, serviced, repaired, or replaced, to keep the plant functioning safely and reliably. If everything is working properly, and *known* to be within acceptable and standardized tolerances, then the plant remains "alive" and its operational life is sustained and continues. In other words, the sociotechnical system of maintenance activities is a significant determinate of the overall life cycle of the system. I would maintain that

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[37] Vinsel 2015, 868.
[38] Blanchard, Verma, and Peterson 1995, 15.
[39] U.S. Nuclear Regulatory Commission 1991, 31306.

studying maintenance, over the system's life cycle, has the ability to make the system more legible. Specifically, by examining maintenance, we can attempt to make visible what risks the system maintainers are constructing and what they are considering as the functioning life span of their technological systems. As the system comes to life, the maintainers, like the operators, become close-in experts of a real- world functioning system. Firsthand, they observe how well the system, as designed, holds up in its operational environment. For example, by happenstance, while performing an unrelated maintenance task, a maintainer may discover metal fragments in a hydraulic pump. Perhaps the pump was designed to undergo periodic inspections every 12 months, but the fragments were found, through maintenance activities, after only six months of operations. Is this a one-time failure or an indication of a deficiency either in mechanical design or in estimation of inspection frequency based upon assumptions of mean-time-between-failures? Or, maintainers could learn that the periodic removal, for inspection, of a component puts undue strain on the electrical connectors of an adjacent component and after several cycles of removal the adjacent component fails. Maintenance, conceptually (and literally) opens the sociotechnical system's "black boxes."[40] [41] It allows the investigator to peer over the maintainer's shoulder to inspect the black box mechanisms acting on inputs and producing outputs (or, in my research, to examine maintenance regulations and associated documents).

[40] Latour 1987.
[41] Mackenzie 1990.

Effective maintenance is all the more important if we do not view system life cycle as moving deterministically from concept, to growth, to consolidation and finally to system maturity; without much said about end-of-life.[42] David Edgerton reconstructs the typical view of technologies from that limited to a history of invention and innovation to one of "technology-in-use."[43] He argues that technologies are not simply replaced by the next invention and innovation, but continue to exist and be used with the new. Edgerton sees that, "We worked with old and new things, with hammers and electric drills. In use-centered history technologies do not only appear they also disappear and reappear and mix and match across the centuries."[44] Technologies are continually in movement, with their end-of-life phase sometimes an indistinct concept. Edgerton considers the life of technologies ranging from those that we can literally hold in one hand (a hammer) to those that cover acres of land (a nuclear power plant). In this study I am considering the life of the latter; large technological systems. With those systems in mind I will later describe and argue how maintenance must *run with* the system, as it is used, to keep it not only functioning, but to keep its location in life legible.

[42] Starr and Rudman 1973.
[43] Edgerton 2007, Introduction. Kindle.
[44] Edgerton 2007, Introduction. Kindle.

Large Technological Systems - End-of-Life

Thomas Hughes said that large technological systems “[contain] messy, complex, problem solving components. They are both socially constructed and society shaping.”[45] Hughes emphasizes that these are all *systems* with each of its constituent artifacts “functioning as a component [that interacts] with other artifacts, all of which contribute directly or through other components to the common system goal.”[46] Additionally, Hughes stresses, “because components of a technological system interact, their characteristics derive from the system.”[47] This is key to understanding that the parts of systems, whether they are hardware, software, policies, methods or people, are not independent actors, but are *system components* that exist functionally only within the context of the system. We must realize that to effectively and safely make changes to the system we must assess and make those changes to the *system* components and not view them independently of the system. Due to the scale and complexity of LTSs, such as nuclear power plants, some system components, and their inherent interactions, may not be visible or even known and can leave us with dangerous gaps of knowledge. These gaps of knowledge are not limited to the typically described mechanics and operations of a complex system, but includes its associated, and coupled, maintenance programs, logistics systems, and their knowledge environments;

[45] Hughes 1987, 51.
[46] Hughes 1987, 51.
[47] Hughes 1987, 52.

all which are intertwined with a systems operational life and, most significant for my examination, its end-of-life.

Hughes does not address end-of-life in his description of the life-cycle of an LTS. He describes the development of a typical LTS in what he calls a "pattern of evolution" that moves from invention, development and innovation to growth, competition and consolidation and decline.[48] I propose to extend Hughes' pattern of evolution by building the concept of system end-of-life. First, what does it mean for a system to be at end-of-life? The idea of end-of-life is commonly thought of, almost literally, as a point in time such as the decommissioning of a nuclear power plant. Even though the decommissioning phase can take decades it seems to be generally thought of as a singular event occurring when the reactor is shutdown. I would argue that end-of-life is often a lengthy phase can begin well before the shutdown event, and even well before a decision is made to prepare for the shutdown. The end-of-life phase could, potentially, begin *its life* without the knowledge of the system operators. Hughes hinted at this condition when he talked of the system entering stasis and decline. At this stage, the operators are maintaining a mature, steady state system. Second, how can the system operators know when they have entered the end-of-life stage? We can look back to the phases of Hughes' evolution and construct end-of-life warning indicators by asking: Is the system being advanced through continual development? Are parts available? Is there an effective logistics supply chain supporting the system? Are personnel with the required education and technical skills available and willing to work the system? Can

[48] Bijker, Hughes, and Pinch 1987, 56.

the system be effectively maintained in order to operate safely and reliably? Is the system still solving a problem by providing a needed product or service?

A system may still be solving a problem, e.g. generation of electricity, but this may be the old problem as originally defined. As the system (the problem's solution) has aged and changed so could have the problem. The new problem to solve may now be the clean generation of electricity. If the system is not solving the new problem then it has become an operating, but static machine, with parts being replaced without significant improvements. Additionally, over time and through infinite changes, the system may become too complex and convoluted to effectively and safely maintain. In the absence of the creation of innovative ways to improve, expand, and use the existing technology's capabilities, the system has reached a steady-state of existence with perhaps unknown levels of safety. At the beginning of the end-of-life phase the system may still have many more years of operational life, but recognizing end-of-life can assist system owners in addressing inherent risks and planning for the future. Adding the end-of-life phase, with appropriate indicating methods, to LTS theory, can assist in providing for a better and safer system lifecycle.

Finally, with the end-of-life component of the LTS theory in mind, how can we assess the current nuclear power plants in the U.S.? This is important, as the NRC is beginning to extend the licensing of reactors for an additional twenty years beyond their original forty-year lifespan and has processes in place to license plants for up to eighty years.[49] Assessment means understanding of the power plants as Hughes relates operations research expert Russell Ackoff's thoughts on system comprehension:

> In the machine age…mechanical devices could be understood…through…problem solving as taught in engineering schools. Because the number of variables were…constrained, problems could be reduced to quantitative dimensions. Problem solvers assumed that they fully understood a machine or a machinelike bureaucratic organization.[50]

The current nuclear power plants were conceived of as machine-age technologies. After the 1979 accident at Three Mile Island the U.S. nuclear industry realized it could not operate nuclear power systems with the same production mentality as coal and oil systems.[51] Nuclear requires Ackoff's broad and interdisciplinary "synthesis" of knowledges and experiences to come closer to "systems-age" understanding and safer system control.[52] Our nuclear power plants may be machine-age artifacts operating in end-of-life stasis. With an LTS theory that integrates systems-age thinking and a recognition that systems have finite life spans, we can better deal with current end-of-life systems and also posture ourselves to construct, from inception, future systems, that are physically, organizationally, politically, and socially conducive to efficient and safe retirement.

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[49] U.S. Nuclear Regulatory Commission 2006.
[50] Hughes 2004, 78.
[51] Rees 1994.
[52] Hughes 2004, 78.

Normal Technology and Normal Design

In the four decades before the Maintenance Rule became a part of the U.S. nuclear power industrial-regulatory environment, the U.S. had put nuclear reactor technology into use for several purposes. It was atoms for the Cold War, creating plutonium for nuclear weapons. It was atoms for national prestige and its international sociopolitical power. It was Atoms for Peace with Eisenhower's proposal "to provide abundant electrical energy in the power-starved areas of the world."[53] For the U.S. utility companies it eventually became atoms for American factories and homes; Eisenhower's atoms for domestic power and light. Not long after the AEC's and Rickover's demonstration, with the Duquesne Light Company's Shippingport Atomic Power Station, of putting electricity on the Pennsylvania grid, power plants were being built around nuclear reactors. Train loads of coal would no longer slowly roll into the plants to fire their boilers. Now, the energy released from the engineered splitting of uranium atoms would heat water, produce steam, and spin the plant's electric dynamos. Less the fission heat, this was the same type of technological system that had been in use since Edison, in 1882, had fired a coal boiler in New York City to illuminate his incandescent lightbulbs.[54] Over the decades, this power generation system had become the norm. It was what Edward Constant called "normal technology" or "what technological communities usually do."[55]

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[53] Eisenhower 1953.
[54] Hirsh 1989.
[55] Constant 1980, 10.

What the technological communities usually did was to plan and build power plants with three primary component systems: the boiler/steam generator, the steam turbine, and the electrical generator.[56] In his study of aeronautical engineering, *What Engineers Know and How They Know It*, Walter Vincenti extended (Vincenti's description) Constant's concept to "normal design" which is "the design involved in such normal technology."[57] Vincenti described normal design and how it informs technology construction:

"The engineer involved in such design knows at the outset how the device in question works, what are its customary features, and that, if properly designed along such lines, it has a good likelihood of accomplishing the desired task."[58]

The power plant engineers knew what the design of a power plant should be and how it worked in practice. The boiler/steam generator transferred heat from burning coal to water and then turned it into high-pressure steam. The steam spun a bladed turbine that in turn drove an electrical generator to produce electricity. This was a cycle of fuel combustion to heat, to heat transfer, to mechanical energy transformation, and finally to electron flow. It was a well understood technological system that practically and economically generated electricity and business revenue for power utilities. This plant design made up the normal technical landscape of power production when the United States began to consider nuclear reactors as an alternative technology to fire

[56] Hirsh 1989.
[57] Vincenti 1990, 7.
[58] Vincenti 1990, 7.

boiler/steam generators. Would the use of nuclear reactors change that normal landscape?

In his thinking on normal design and normal technology, Vincenti introduced Michael Polanyi's thoughts on the "operational principle" of a device (in our case a steam power plant) that specifies "how its characteristic parts…fulfill their special function in combining to an overall operation which achieves the purpose of the machine."[59] Vincenti introduced the idea of "normal configuration" that he described as "the general shape and arrangement that are commonly agreed to best embody the operational principle."[60] He defined normal design and technology as the "shared operational principle and normal configuration…of a device."[61] Even with nuclear fission, rather than coal (or other fossil based carbon fuels) heating water in a boiler/steam generator, the operational principle of an electrical power plant appeared to remain the same. There was still the heating of water to produce steam, to transform into mechanical energy, to generate electricity. The high temperature, high-pressure, boiler/steam generators, the high-speed, precision turbines, and high-speed, gas cooled electrical generators remained the normal configuration. Therefore, with this known and established operational principle, the architects of nuclear fired power plants continued to build them with their normal design to this normal configuration. The plants were still perceived as normal technology by their builders, and the utilities who operated them, but there were two significant and related differences.

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[59] Polanyi 1958, 328.
[60] Vincenti 1990, 209.
[61] Vincenti 1990, 210.

First, while the overall operational principle of coal (fossil) and nuclear power plants appeared to remain the same, the operational principle of heating the boiler/steam generators in coal and nuclear plants was radically different, and significant. In the framework of systems and sub-systems, the boiler/steam generator was an extremely complex system in itself within the overall system of the power plant. Vincenti noted that, "Operational principles also exist for the components within a device."[62] The operational principle of producing heat by the nuclear fission of uranium atoms versus the molecular burning of coal is fundamentally different. Furthermore, the resultant energy outputs are also fundamentally incomparable, with "the fission of each nucleus [producing] 25 million times more energy than the combustion of an atom of carbon."[63] Second, returning our attention to the perceived normality of the overall power plant system, the operational principle of nuclear fission was not contained in the boiler/steam generator sub-system of the overall power plant. It also extended to all other systems of a normally designed (traditional conventionally fueled) plant to include the turbine systems, generators and all associated supporting SSCs. The balance-of-plant (BOP), that which is outside the nuclear system, had also become nuclear in its operational principle. This new nuclear operational principle required a new normal (nuclear) configuration and design — to also include the principle of nuclear maintenance. Nuclear maintenance, in a new normal configuration, became a technological component required for the safe and reliable functioning of a nuclear power plant.

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[62] Vincenti 1990, 209.
[63] Garwin and Charpak 2001, 35.

The electric utility companies were viewing nuclear power plants as familiar, normal technology. They were operating nuclear plants using the operational principle and normal configuration for fossil fuel plants. Vicenti pointed out that, "The operational principle also, in effect, defines a device."[64] By using nuclear fission to heat water, the device (the entire power plant) was redefined; it had become a nuclear entity. The power industry was designing to the incorrect operational principle. The result of this misalignment was the eventual recognition during twenty years of operational experience and culminating in the TMI-2 accident, that nuclear steam power plants require much more knowledge to safely and reliably operate than their fossil fueled cousins. The NRC recognized that a critical knowledge producer, and required component of a nuclear power plant, is a comprehensive maintenance program. The Maintenance Rule became the regulatory construction tool that initiated the building of maintenance programs as critical safety components of nuclear power plants. The Rule reworked maintenance to fit the nuclear operational principle and what was to become a normal technological configuration.

NRC Primary Sources

My source for primary historical documents was the NRC's Public Document Room (PDR) located at NRC headquarters in Rockville, Maryland. The PDRs staff of technical librarians were invaluable in assisting me in locating NRC and nuclear industry

[64] Vincenti 1990, 209.

documents related to the history, development and implementation of 10 CFR 50.65, *Monitoring the Effectiveness of Maintenance at Nuclear Power Plants* (the Maintenance Rule). The documents included: 1) NUREG publications prepared by the NRC staff or contractors in the form of reports, decisions and research, 2) Transcripts from Commission meetings and public workshops, 3) NRC Regulatory Guides, 4) SECY papers prepared by the NRC staff to provide information to the Commissioners, 5) Inspection manuals and procedures, 6) Commission correspondence and, 7) industry documents such as technical guidelines and correspondence to the NRC.

The documents are cataloged and made availability through the NRC's Agencywide Documents Access and Management System (ADAMS). The system provides access to the NRC's Publicly Available Records System (PARS) Library and the Public Legacy Library. ADAMS is available and searchable online where most documents dated from the early 1990s can be easily downloaded from the PARS Library. My historical look at the Maintenance Rule required access to the Public Legacy Library since all early activities in its development occurred in the 1980s. Document citations were available in ADAMS, but the documents only existed in physical microfiche stored in the PDR at Rockville, MD. This required numerous trips to the PDR and hours to review microfiche, scan the film documents, and digitally save and convert them to a searchable format.

Interviews

I conducted eight, one hour, audio recorded interviews for this research. The interviews were to help me better understand nuclear workers professional experience and personal views of the Maintenance Rule. I interviewed people previously or currently with the NRC and the nuclear power industry. I wished to get a feel for the Maintenance Rule beyond how it is documented to how it was practically developed and implemented. What is it actually doing in practice?

All of the interviewees had either nuclear engineering or operator training and had been licensed operators at one time in their careers. All had either engineering, operations, or maintenance management experience to include areas such as risk management, human performance management and instrument and control maintenance. Two had executive level experience within industry. Two had started their careers in the U.S. nuclear Navy and one began their professional career when the Atomic Energy Commission (AEC) was still in existence in the late 1960s. Two of the eight interviewees work for the U.S. Nuclear Regulatory Commission (NRC), three work for electric utilities, two work for organizations that advocate for and support the nuclear industry (one was recently retired) and one works for a scientific association outside of the nuclear industry or the NRC.

I asked approximately forty questions in five general categories: 1) history of the maintenance rule, 2) implementation of the maintenance rule, 3) pivotal events (Three Mile Island, Chernobyl, and Fukushima), 4) redefining maintenance (changes in maintenance) and, 5) redefining reliability (effects of the maintenance rule on power plants). These areas were to generally frame the dissertation, but I found it was not a precise fit with, for example, pivotal events limited to Three Mile Island. I did not need to ask the questions by rote, but found that the interviewees would typically discuss the topic of questions without prompting once we were discussing a particular category.

All of the interviews went very smoothly, and I found the interviewees extremely professional and knowledgeable and eager to talk about their experiences and how things work at the plant, management, and government levels. They appeared to be candid and honest in their discussions and I cross-checked that among interviews. I personally transcribed each interview. All of the interviewees were kept anonymous.

Chapter 2
History of the Maintenance Rule

Atomic Maintenance

In the first decade after Dresden Unit 1 began commercial operations, fifteen more power reactors were brought online by the electric utilities in the United States and they ordered many more.[1] By 1974 there were 191 reactors "under construction, under licensing review, on order, or announced by the utilities."[2] This rapid population increase of reactors was significant and so was the increasing size of the reactors. For comparison, Shippingport Atomic Power Station was built with a 90 MWe power output while the Tennessee Valley Authority's (TVA) Brown's Ferry Unit 1, in Alabama, had a power output of 1,065 MWe – over a tenfold increase. It was one of the first reactors designed to produce over 1,000 MWes. To produce that level of power Brown's Ferry required a much larger uranium fuel load; that meant the more fuel being "burned" the greater the heat generated. In her 1979 Rand Corporation study of nuclear power regulation and safety, Elizabeth Rolph pointed out that "the decay heat (heat from the fission products when the reactor is "off") from the 1,065 MWe Brown's Ferry reactor…almost equaled Shippingport's full power output."[3] Therefore, in the event of a

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1 Rolph 1979.
2 Walker 2004, 8.
3 Rolph 1979, 79.

loss of coolant accident more emergency water was needed, and more rapidly, than for earlier, smaller reactors.[4] Safety and emergency systems had to be increasingly reliable and available. As the number and size of reactors (and the probability of an accident) increased so did the need, whether fully recognized or not, for reliably maintained systems.

What led up to the realization by the U.S. government and some within the nuclear industry that atomic plants were not as safe as they needed to be, and that a substantial reason was the lack of effective formal maintenance programs? What did the early nuclear organizational and technical environment look like that shaped the risks of the regulator? This was an environment where the regulator, the Atomic Energy Commission (AEC), "wanted private industry to take the lead in achieving commercial competitive nuclear energy."[5] The agency providing regulatory control over the commercial nuclear industry was also promoting nuclear power. The AEC was creating regulations to rapidly advance safe nuclear power technology in the United States, but "without imposing excessive requirements that would discourage private investment in nuclear technology."[6] This pressure from the government to have a successful commercial nuclear power industry in the United States may have also contributed to the electric utility companies pressing forward without adequate knowledge of nuclear design for safe and reliable operations and maintenance. To explore these questions, I

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[4] Rolph 1979.
[5] Walker 1992, 10.
[6] Walker 1992, 10.

will reexamine the traditional story of the commercial atom as the United States worked to develop a system of governing laws, regulatory controls within economic constraints.

Building Atoms of Power

How did the fleet of U.S. commercial nuclear power plants arrive at a state where the government regulator determined that inadequate maintenance was a serious threat to safe reactor operation? Were the U.S. atomic power plants born with a system of ineffective maintenance? To understand how the U.S. commercial nuclear power environment was initially shaped by postwar domestic and geopolitical conditions I have drawn on work by Brian Balogh,[7] Richard Hewlett and Francis Duncan,[8] Duncan,[9] and Theodore Rockwell.[10] Examining their description of events in the decade and a half after World War II, I have constructed a logical, historical line of development that the nuclear power system traveled from the late 1940s to the early 1960s. I have placed the line's origin point at end of WWII marked by the completion of the Manhattan Project in 1945 and its endpoint where the first privately constructed power plant began operation in the U.S. in 1959. This developmental line conceptually ties together several events and conditions that constructed and shaped the operations, maintenance, and economic management philosophies of the United States nuclear power industry. It was this as-built sociotechnical infrastructure that was in place as the

[7] Balogh 1991.
[8] Hewlett and Duncan 1974.
[9] Duncan 1990.
[10] Rockwell 1992.

AEC, and later the NRC, began to assess the safety of nuclear power plants and the probabilities of system failures.

World War II

In his 02 August 1939 letter to Franklin D. Roosevelt (briefed to Roosevelt on 11 October 1939),[11] Albert Einstein began by telling the U.S. President of the potential of uranium nuclear chain reactions as becoming an "important source of energy," but the letter's main thrust was to inform the American leader and the U.S. government of wartime use of "this new phenomena."[12] With the world on the verge of war, research concerning energy production was not further spoken to. Einstein's letter described that uranium chain reactions "would also lead to the construction of…extremely powerful bombs" and warned that Germany was conducting research and had "stopped the sale of uranium from Czechoslovakian mines which she has taken over."[13] With Germany's invasion of Poland on 01 September 1939 World War II had begun in Europe and the letter prompted Roosevelt to establish a research committee on uranium. Two years later, in the Summer of 1942, after the American entry into the war, the Manhattan project was started. Under this massive U.S. Army Corps of Engineers managed project, the destructive power of the atom was rapidly engineered under wartime conditions. The Manhattan project's final product was horrifically demonstrated to the

[11] Gosling 2010, vii.
[12] Einstein 1939, 1.
[13] Einstein 1939, 1.

world, by the United States, with the destruction of two Japanese cities with atomic fission bombs.

The Manhattan Project

The U.S. wartime development of the atomic bomb, the ultimate technology of obliteration, required the marshaling of unprecedented levels of scientific, engineering, management, training, and production ingenuity to this singular task. The all-encompassing motivational force driving its development was the expediency of producing a machine of unequivocal destruction before the enemy could do the same. To construct the power of the atomic bomb, cost and political will were not constraints. With the end of World War II any anticipated peace constraints did not materialize as the two major victors, the United States and the Soviet Union, postured, and continued development of more, and more advanced, atomic weapon *systems* (the Soviet Union would explode its first atom bomb in 1949). In these immediate post-war years nuclear systems for power production were a secondary priority, but their time would come as the Cold War rumbled to life with the explosions of atomic tests and the construction of many other large technological military systems. But, even with the U.S. government investing tremendously in its Cold War military mobilization, when it eventually turned its attention toward non-military applications of the atom the government did not elicit immediate interest from the commercial power industry.

National Strategy and Atomic Containment

Why would the post-war U.S. commercial utility industry *not* be interested or motivated to use the newly engineered atomic fission to power its electricity generator plants? The Manhattan Project had produced the engineering and massive industrial management technologies for the production of atomic fuel and to enable, on command, the uncontrolled neutron chain reaction of the atomic bomb.[14] It might have seemed inevitable that after the war there would have been a rapid investment of resources by the government and commercial industry to pursue controlled fission for power production. But, even with post-war atomic weapons development taking priority there were two overarching reasons that restrained U.S. companies from actively pursuing nuclear for commercial use: restricted information and the economic bottom line.

The Atomic Energy Act – 1946

With the end of World War II, and the existence of the atom bomb no longer a military secret, the U.S. moved rapidly to bring its atomic information and industrial atomic infrastructure of the military's Manhattan Project under structured civilian control. The Atomic Energy Act of 1946 instituted U.S. national law and policy "for the development and control of atomic energy."[15] The act, put into effect 01 January 1947, established the Atomic Energy Commission (AEC) with five civilian commissioners. It

[14] Garwin and Charpak 2001.
[15] U.S. Atomic Energy Commission 1946, 1.

also created and put into place the Joint Committee on Atomic Energy (JCAE) composed of nine Senators and nine Congressmen who were charged to oversee the Commission. The Act, the Commission, and the JCAE formed the government legislative and regulatory infrastructure for all atomic technologies for both military and civilian uses. With, at the time, concern over loss of atomic weapons secrets to *all* foreign nations the act implemented extraordinarily strong constraints on all aspects of atomic materials and knowledge of any kind.

The newly created civilian Commission now had "ownership"[16] of America's nuclear materials and information to include nine plutonium type bombs; the world's entire stockpile of atomic weapons.[17] The commission would control all atomic research and development for both military and, yet to be determined, civilian use. This encompassed the "control of the production, ownership, and use of fissionable material to assure the common defense and security and to insure the broadest possible exploitation of the fields."[18] The Act laid down the first foundational planks for control of America's nuclear weapon and nuclear power technological systems. The law provided an initial strategic foundation for the secrecy shrouded weapons development as it moved from a shooting war project that invented the atom bomb itself to a, soon to be realized, long term strategic weapons system development and production regime. Like the Manhattan project the Atomic Energy Act kept the control and management of the regime firmly in the federal government's purview while moving it from military to civilian

[16] U.S. Atomic Energy Commission 1946, 6.
[17] Schwartz 1998.
[18] U.S. Atomic Energy Commission 1946, 1.

control. The military was obviously the only customer of the atom bomb and the forthcoming atomic weapons systems, while customers for atomic power were found by the government to be more difficult to acquire. This was attributable much to the effects of the Act itself.

The Act specified two primary areas that instituted atomic containment: control of materials, and control of information. Materials meant fissionable material in the form of "plutonium, uranium enriched to isotope 235, [and] any other material which the Commission determines to be capable of releasing substantial quantities of energy through nuclear chain reaction."[19] The Act prescribed ownership and control of these fissionable materials to the Commission. It also made it "unlawful for any person…to…possess or transfer any fissionable material except as authorized by the Commission."[20] The elemental atom itself was contained by law. The second area of control pertained to atomic information or "restricted data."[21] This formalized designation of information meant "all data concerning the manufacture or utilization of atomic weapons, the production of fissionable material, or the use of fissionable material in the production of power."[22] Finally, the President of the United States transferred all atomic property to the Commission which was essentially an all-encompassing act of control and containment:[23]

(1) All fissionable material; all atomic weapons and parts thereof; all facilities, equipment, and materials for the processing, production, or utilization of fissionable material or atomic energy; all

[19] U.S. Atomic Energy Commission 1946, 6.
[20] U.S. Atomic Energy Commission 1946, 6.
[21] U.S. Atomic Energy Commission 1946, 12.
[22] U.S. Atomic Energy Commission 1946, 13.
[23] U.S. Atomic Energy Commission 1946, 12.

processes and technical information of any kind, and the source thereof (including data, drawings, specifications, patents, patent applications, and other sources (relating to the processing, production, or utilization of fissionable material or atomic energy; and all contracts, agreements, leases, patents, applications for patents, inventions and discoveries (whether patented or unpainted), and other rights of any kind concerning any such items;

(2) All facilities, equipment, and materials, devoted primarily to atomic energy research and development, and

(3) Such other property owned or in the custody or control. of the Manhattan Engineer District or other Government agencies as the President may determine.

These three, lengthy, legally binding sentences *contained* not only the elemental atom, but the fundamental atomic knowledge that was either existing or *could exist* in the future. This was the Act's construction of restricted data. If you thought of atomic knowledge and wrote it down, it could potentially be *inherently* classified and therefore automatically be the property of the U.S. government. The government could literally own and classify atomic information upon its inception and without the requirement for explicit classification by a government authority; restricted data was "born classified."[24] Ruebhausen and von Mehren referred to this control of future knowledge with some poetic flair by describing it as "the uncounted atomic products still in the womb of time."[25]

This law, intended to maintain America's monopoly on atomic weapons, was soon recognized by the government and private industry to be overly restrictive in guarding not only atomic weapons secrets, but locking up general atomic information as the U.S.

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[24] Schwartz 1998, 443.
[25] Ruebhausen and von Mehren 1953, 1450.

government began to look toward developing privately owned and operated commercial atomic power plants. In August 1952, Carl Durham, Chairman of the Joint Committee on Atomic Energy, in a letter to the Atomic Energy Commission, expressed the Committee's interest in "private industrial firms [that are] exploring the possibility of offering to build reactors wholly or partly at their own expense, with the dual purpose of producing power for sale to the public and plutonium for sale to the government."[26] Atomic technology was dual use and could be crafted into either a military sword or a civilian plowshare. While the equivalent of atomic foundries were gradually building bombs of greater yield and designing them to be delivered by military aircraft of increasing range and speed, the technology of commercial power reactors was being *instantly* subsumed and restricted by the government. It was as if a sheet of paper, written with some new bit of atomic knowledge, was snatched away and claimed by the AEC as soon as the pen was lifted.

In his study of U.S. commercial nuclear power policy, *Chain Reaction*,[27] Brian Balogh shows that in this immediate post-war period overall nuclear policy was still finding its footing on its strategy planks for bombs and power. Even with the development of atomic weapons, the extent of use of nuclear power systems for the military was not yet completely solidified. The U.S. Navy enthusiastically embraced nuclear propulsion for its submarines. Nuclear power transformed the former submersibles, craft that could temporarily submerge, to true submarines that could

[26] Joint Committee on Atomic Energy 1952, iii.
[27] Balogh 1991.

remain hidden underwater virtually indefinitely and travel at high speed with unlimited range.[28] The atom was truly a revolutionary technology for the Navy's silent and stealthy service. In contrast, the Navy did not see the value of nuclear power for its surface warships. Stealthiness beneath the surface of the oceans was not a capability a nuclear reactor could provide an aircraft carrier, cruiser or destroyer so nuclear propulsion was not immediately seen as important for the surface fleet. The Navy was comfortable with its established fifty-year-old technological system of oil fueled ships and supporting supply infrastructure that allowed it to patrol the world's oceans.[29] Beyond the nuclear technical solution not meeting a major naval mission requirement or a known operational shortfall, the cost of nuclear driven surface ships was projected to be extraordinarily high compared to conventionally powered ships.[30] In the early 1950s plans for building expensive reactors for aircraft carriers were scrapped while the Navy's Admiral Hyman G. Rickover, often called the "father of the nuclear navy,"[31] rapidly pursued the development of pressurized-water-reactors for submarines. The first nuclear powered carrier, U.S.S. Enterprise, was not commissioned until 1961 due to opposition by the Navy leadership itself who saw that a conventionally powered carrier could be built for approximately $190 million while Enterprise was estimated at nearly $315 million.[32] Nuclear engineering costs were also high for commercial power plants compared to conventionally fueled systems and faced similar internal opposition from the electric utility companies due to cost. This high cost became evident early on. The

[28] Balogh 1991; Duncan 1990.
[29] Dahl 2001; Duncan 1990.
[30] Balogh 1991; Duncan 1990; Rockwell 1992.
[31] Duncan 1990, xvii.
[32] Duncan 1990.

first plant to be connected to the power grid as a full-time generator of power was the Shippinport demonstration plant and Admiral Rickover estimated that Shippingport was "more than ten times the cost of a conventionally fueled plants."[33] The new atomic technology did not yet readily fit into either military or commercial power applications.

Containment by Economics

By the early 1950s electric utility companies in the United States had nearly half a century of experience heating water with coal, to make steam, to spin electricity producing turbine generators. The commercial power industry had made steady advances in improving the efficiency, and thus lowering operating costs, of fossil fuel burning furnaces, high pressure steam producing boilers, faster spinning turbines, generators, high-voltage transmission systems, and how to market and sell electricity.[34] At the time, the industry understood the technologies and the economics of their fossil fuel electricity production system from end-to-end. When the prospect of using atomic fuel began to materialize the industry was disinterested at best.

Atomic vs. Conventional Power Plant Costs

With the end of World War II, the U.S. began to grapple with securing its atomic knowledge and practical experience beyond that pertaining just to nuclear weapons.

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[33] Balogh 1991, 106.
[34] Hirsh 1989.

With interest by the academic research community and private companies eyeing potential government contracts, it was as early as 1946 that the U.S. declassified limited technical aspects concerning the "design and operating characteristics of small experimental piles in which enriched material or heavy water is used."[35] Non-weapons specific nuclear technologies were also ensnared by the Atomic Energy Act of 1946, but this containment of knowledge was not absolute. Even while the government pressed ahead with weapons research it also allowed, nearly immediately, the release of information concerning non-military atomic technologies. A major purpose the Act was to put into a place a program "for the control of scientific and technical information which will permit the dissemination of such information to encourage scientific progress, and for the sharing on. a reciprocal basis of information concerning the practical industrial application of atomic energy as soon as effective and enforceable safeguards against its use for destructive purposes can be devised."[36] The information was made available to industry, but only under the constraints of classified government control. President Truman signed the Act into law in 1946 and it went into effect on New Year's Day 1947 giving birth to the Atomic Energy Commission along with the conception of born classified atomic knowledge.

Estimates of costs, feasibility, and risk, are based upon experience. With government restrictions encompassing both atomic technology and knowledge, private industry had no legal way to begin to independently build experience. Knowledge containment also prevented industry from even *theorizing* (outside of work contracted

[35] U.S. Department of Energy 2001.
[36] U.S. Atomic Energy Commission 1946, 1.

by the government) about the atom and its practical uses. The U.S. government's monopoly had become a self-imposed structural anchor that constrained the U.S. from effectively moving forward by mobilizing commercially driven resources, while at the same time the American public's perception of the future of atomic technology was one of unconstrained benefits.

Smyth Report - August 1945

Before the end of WWII, the U.S. was looking ahead to post-war uses of atomic technologies. In 1944, less than two years after Fermi initiated the world's first fission of the atom and a year before the first atomic explosion, U.S. Army Major General Leslie Groves, commander of the Manhattan project, formed a committee to assess the potential of advancing nuclear technology to areas beyond that for military use. The committee members agreed that the growth of nuclear technologies would occur, but the building of a nuclear industry was one where "growth would be slow over a period of many years."[37] Their assessment was based upon what they were learning and the difficulties they had yet to overcome. There was much unknown about the practicalities of producing nuclear power since the project's focus was on creation of fissionable material and ultimately an atomic weapon. This conclusion was made public as part of the 1945 "Smyth Report" to the American public. The report was the contemporaneous government history of the development of the atomic bomb. It was researched and written by Dr. Henry D. Smyth who felt that, "the possibilities of the atomic energy, and

[37] Smyth 1945, 225.

particularly of the bomb, were so important that the political decisions which would have to be made ought to be based on the widest possible dissemination of information."[38] Its transparent detailing of the Manhattan project, that had been a top secret wartime program just five days before the report's publication, helped to fuel the public's imagination and perception as to what their country's national drive, scientific brilliance, and engineering ingenuity could accomplish. To Americans the invisible atom not only won the war, but had the potential to provide nearly limitless and seemingly magical energy for its high-tech post-war society. The stage was set for the atomic age which would define the Cold War and be major factor in the West East competition for socio-political power. The minds of the American citizens were being shaped by the promise of atomic power.

The American Public

The popular press published all manner of articles extolling the amazing benefits of the new atomic science. The A.C Gilbert Company of New Haven Connecticut, the longtime maker of home chemistry sets for young people, moved into the atomic age with their nicely boxed (and expensive at $50) "Atomic Energy Lab." The lab featured a cloud chamber, an experiment manual and radioactive source material for alpha, beta and gamma rays. It even included a coupon to be used to replace the radiation emitters in one to fifty years. Gilbert was obviously ready for the current and next generation of nuclear scientists and engineers. A 1953 article in The Harvard Law Review recognized

[38] Smyth 1945, 301.

the popular perception of atomic technology by pointing out how people had "the fantasy of a brave new world in which an "atomic pill" would propel the space ships of science fiction."[39] Even in the time of duck-and-cover civil defense drills, American popular culture had slightly split the atom away from military bombs and attached it to civilian science, education, and mundane, but decidedly modern, daily life. The atomic age was *expected* by people to bring them benefits. U.S. citizens *expected* America to be leading the world into the atomic age. Furthermore, the U.S. government was working to have its allies and, more importantly, its potential Cold War allies to expect America to lead the West. Walter Bedell Smith, U.S. Under Secretary of State, underscored the importance of America leading the world in atomic technology:

"It would be very damaging to the position of the United States if another country were to be first in this field of endeavor, and it would be especially damaging if the Soviet Union were to precede us in the development of atomic power. If this were to happen, the Soviet Union would cite their achievement as proof of their propaganda line that the United States is interested in atomic energy only for destructive purposes while the Soviet Union is interested in developing it for peaceful purposes."[40]

The "need" for atomic power was building momentum and would overcome cost and technical concerns and constraints even those voiced by government and ultimately industry. The commercial industry that would have to build, operate and maintain the system. Commercial nuclear power was treated by the government as a non-military weapon in the Cold War arsenal and was initially funded as such with Shippingport.

[39] Ruebhausen and von Mehren 1953, 1450.
[40] Joint Committee on Atomic Energy 1953, 63.

When the private electric utilities began to build and finance the plants themselves the high costs and the requirement to be profitable were not compatible. The military mission of never failing, always fully-mission-capable (FMC), was sustainable since costs were not a significant constraint; the profit was being FMC as a national strategy. The utilities were forced to cut costs and therefore, more comprehensive maintenance, needed for nuclear plants, was not part of the profit producing system.

Atomic Energy Commission (Hafstad) – 1951

The government recognized that the American taxpayer perceived that atomic technology would soon easily power everything from their toasters to their automobiles at virtually no cost. Interestingly, with that recognition, the Atomic Energy Commission publicly pointed out that the atom was not the magical solution for the public's desire for unlimited and cost free power. The AEC, knowing that the cost of commercial nuclear power was at best very speculative and was estimated to be tremendously expensive, pressed to inform the public that the economies of the atom would most likely not be realized for at least one or two decades. In an April 1951 article published in the American science magazine *Scientific American*, the AEC's Director of the Division of Reactor Development, Lawrence Hafstad, wrote that nuclear reactors were "large, complicated, expensive and controversial" and that "some of [their] proposed uses are strictly figments of the imagination."[41] With the purpose to have Americans "begin to

[41] Hafstad 1951, 43.

feel at home with these new machines of our civilization,"[42] Hafstad described the potential for development of various types of nuclear reactors and their civilian uses in addition to the production of plutonium for the military. At the time, worldwide sources of uranium, sufficient enough to fuel industrial reactors, were in doubt so civilian use also meant looking at the development of breeder reactors that produced more fissionable material than they burned. Reactors would not only generate power, but would simultaneously produce marketable product. Also, while the government had experience building and operating reactors for plutonium production, they had none with reactors designed for the high heat required to produce electricity; none existed. Without suitable reactors they could not gain experience to reasonably estimate costs that would encourage investment by industry. The technical was not the primary risk concerning the government, it was the economic viability of nuclear plants and their supporting systems, as Hafstad emphasized:

"Enough technical facts have long been known to assure us that electric power can be produced— if we are willing to pay the price."

"The cost of construction of a nuclear power plant is still essentially unknown."[43]

"Only if and when civilian power can pay its own way, from the uranium mines to the waste-disposal dump, can it truly be said that the civilian atomic power problem will have been solved."[44]

The AEC's limited experience with power production was only gained with Naval mobile reactors; mobile because they were being engineered by the Navy for submarine

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[42] Hafstad 1951, 46.
[43] Hafstad 1951, 47.
[44] Hafstad 1951, 50.

propulsion. Using submarine system reactors to get a sense for the cost of stationary, land-based plants was notional at best. The naval reactors' design was severely restricted by military security needs, size, weight, and stringent safety and reliability requirements of a vessel operating in an extremely hostile environment where over one-hundred men's lives depended upon one-hundred percent reliability of their power plant; a nuclear reactor operating literally feet from their working and living quarters. Hafstad presented the cost of a conventional coal fired power plant as $100 to $150 per kilowatt-hour. The highly engineered and integrated submarine plant was approximately an order of magnitude greater at $1,400 per kilowatt-hour. Hafstad rather optimistically predicted that the $100 to $150 range was potentially achievable for stationary commercial plants if the naval size, safety, and reliability requirements were relaxed in combination with predicted technical advances.[45] Hafstad told the readers of Scientific American that the way forward for commercial nuclear power was to "utilize the profit incentive" and to ensure "industrial people with the know-how and we in Washington have the will and the ingenuity."[46] The absolute government nuclear monopoly, designed and constructed upon weapons and their secrets, was now viewed by the government as being no longer an effective control and development mechanism for non-military nuclear technologies. Using the private enterprise model to advance and propagate nuclear technology was the government's solution, but unknown costs remained a severe constraint.

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[45] Hafstad 1951.
[46] Hafstad 1951, 50.

Joint Committee on Atomic Energy (JCAE) - Atomic Power and Private Enterprise - 82nd Congress - 1952

In 1952 the JCAE, AEC and American industry were jointly grappling with how to expand atomic research and engineering out of the containment of the government monopoly and into the realm of American business. Fundamental to the business discussion was the perceived cost of nuclear plants which, for private enterprise, is a critical and intrinsic component. The atom had to not only produce power, but had to produce profit. In June of 1950 the President of the Monsanto Chemicals Company, Dr. Charles Allen Thomas, a veteran of the Manhattan Project and himself a witness to the first atomic bomb explosion, gave the commencement address at Hobart and William Smith Colleges in Geneva, New York. In his speech he proposed a relationship between the government and American industry where the government would own the material atom, but industry would own the power generated from the atom while being incentivized to produce plutonium and power at competitive prices.[47] Here, strikingly, private industry was engaging directly and emphatically, with the constraints of the Atomic Energy Act by overtly supporting the Act's declaration of policy:

> "the policy of the people of the United States that, subject at all time to the paramount objective of assuring the common defense and security, the development and utilization of atomic energy shall, so far as practicable, be directed at improving the public welfare, increasing the standards of living, strengthening free competition in private enterprise, and promoting world peace."[48]

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[47] Joint Committee on Atomic Energy 1952.
[48] U.S. Atomic Energy Commission 1946.

American utility companies would not only generate electricity, but also produce the most critical component of atomic bombs, and at a profit. Allen presented a conceptual plan that provoked significant players of the U.S. industrial base and the electrical utilities to partner and to propose, "on their own initiative, using their own resources — … development of applications of atomic energy for power purposes."[49] By early 1951 four industry groups had approached the AEC and offered just what Allen had proposed; their own funded research efforts and industrial expertise. Each joint group had an industrial member and an electric utility member. With industry and the power companies interested and willing to invest their own money the AEC established the "Industrial Participation Program" to help ensure "the application of the best available brains to all the important problems of the Commission."[50] With Allen nudging his own industry and AEC accepting private industry's offer, a change in the way of doing nuclear business under the Atomic Energy Act of 1946 was underway. The public and private sectors were reconfiguring their relationship for what was to eventually become regulated reactor business operations.

What would the route to those restructured operations look like? The industrial-electric groups taking part in the program were: 1) Monsanto Chemical Company and Union Electric Company, 2) Dow Chemical Company and Detroit Edison Company, 3) Commonwealth Edison Company and Public Service Company of Northern Illinois, and 4) Pacific Gas and Electric Company and the Bechtel Corporation.[51] Dow and Detroit

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[49] Joint Committee on Atomic Energy 1952, 8.
[50] Joint Committee on Atomic Energy 1952, 8.
[51] Joint Committee on Atomic Energy 1952.

Edison were the most aggressive in their thoughts of changing the government atomic monopoly. Mr. Walker S. Cisler, President of Detroit Edison, emphasized that his company and Dow "would like to build and to operate a commercial sized reactor plant using private capital and without recourse to governmental funds."[52] Cisler's bottom-line optimism was his expectation that there would be a sufficient "market for the excess fuel to meet the requirements for mobile reactors and for the requirements of an expanding nuclear power industry."[53] He was, remarkably, envisioning the use of small power reactors at remote locations to service the military and industries such as oil companies. The excess fuel was to come from breeder reactors that Detroit Edison and Dow advocated. Cisler was proposing that private enterprise both operate and own reactors and fissionable material; something not permitted under the government atomic monopoly. Charles Allen Thomas' own Monsanto Company's proposal was not nearly as ambitious. Monsanto and Union Electric proposed in keeping the atom itself as a government owned commodity. While the non-nuclear power plant would be privately owned and operated the nuclear fuel used and produced by the plant would be owned and controlled by the government. Commonwealth Edison basically proposed that the government would not only own the fissionable material, but also the reactor itself. Edison would only invest in the conventional balance-of-plant facilities and contribute virtually nothing to the care and feeding of the government's atom; for them the government monopoly of the atom would remain.

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[52] Joint Committee on Atomic Energy 1952, 20.
[53] Joint Committee on Atomic Energy 1952, 21.

In the summer of 1952, Carl Durham, Chairman of the Joint Committee on Atomic Energy wrote to Gordon Dean, Chairman of the Atomic Energy Commission. Durham wanted to know how things were going with the Industrial Participation Program so the Committee could report back to the Congress on the program during the next session of Congress. What was the feasibility, technically and economically, of private firms owning and operating reactors for power and plutonium production? Durham thought that an assessment of feasibility should now be at "a point of crystallization."[54] Durham also asked Dean for the Commission's recommended policy on commercial reactors. Dean responded and said that, "Commission policy…should be crystalized to the point where profitable discussions with the Joint Committee are possible by the first of the year."[55] It took the first half of1953, for the AEC to fully crystalize a policy shaped by the proposals of industry groups in the Industrial Participation Program. On 26 May 1953 the AEC presented its policy to the Joint Committee. The Commission described it as policy that was "designed to recognize the development of economic nuclear power as a national objective."[56]

The AEC's "Statement of Policy on Nuclear Power Development" strikingly, in a single page, emphasized the economics of advancing U.S. nuclear knowledge and technology. First, within the policy was an overarching objective that the U.S. must maintain its "leadership in nuclear power development"[57] and now should pursue the goal of "economically competitive nuclear power."[58] Secondly, it called for practical

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[54] Joint Committee on Atomic Energy 1952, III.
[55] Joint Committee on Atomic Energy 1952, III.
[56] Joint Committee on Atomic Energy 1953, 6.
[57] Joint Committee on Atomic Energy 1953, 6.
[58] Joint Committee on Atomic Energy 1953, 6.

nuclear research and development through the building and operating of experimental reactors that would "constitute useful contributions to the design of economic units."[59] Both of these policy points were lawfully feasible within the government containment structure of the Atomic Energy Act of 1946, but the AEC was working to dramatically change that structure to increase the likelihood of developing commercially owned and operated nuclear power. The policy also explicitly advocated for nuclear development participation of groups outside of the Commission to "progress toward economic nuclear power."[60] That statement cracked open the door of the government monopoly containment.

The AEC then swung the door wide by describing the need for "reasonable incentives"[61] for non-government nuclear development participants. They proposed allowing non-government ownership of both nuclear power plants and fissionable material. The nuclear monopoly would be no more with the release of plants and their nuclear fuel to those outside of the government. Even with these fundamental controls of the nuclear monopoly shutdown, the AEC recognized that private enterprise would require further business incentives. The restriction of patents was part of government's containment of atomic knowledge and the economics of owning and commercially using that knowledge. To incentivize private enterprise to invest in and to create a nuclear business the AEC recommended, "more liberal patent rights"[62] for commercial companies. Furthermore, at the time, a significant aspect of discussion in building a

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[59] Joint Committee on Atomic Energy 1953, 6.
[60] Joint Committee on Atomic Energy 1953, 6.
[61] Joint Committee on Atomic Energy 1953, 6.
[62] Joint Committee on Atomic Energy 1953, 6.

business model for commercial nuclear power was if a plant could solely produce power and remain economic without also being economically tied producing plutonium for military purchase.[63] To decouple the explosive from the electric the AEC stated in the policy their intent to move toward a commercial nuclear power system that was "economically independent of Government commitments to purchase weapons-grade plutonium."[64] This would deconstruct dual-use power plants by removing an inherent government subsidy and by pushing private enterprise to themselves develop economical electricity producing nuclear plants. In all, the policy would effectively deconstruct the Atomic Energy Act of 1946, but the AEC was not ready to claim that a private system of commercial nuclear power plants could be generated from the disassembled components of the Act. The Act's Section 7(b) report was not yet ready to be written by the AEC.

The constructors of the Atomic Energy Act of 1946 were forward looking. They had designed and built a strict legal system "for the development and control of atomic energy."[65] The Act was quite effective in implementing a government monopoly to contain the atom, but it was not built to necessarily last indefinitely. The government anticipated inevitable change as it advanced its nuclear knowledge and determined how the technology would affect the country and world relations. The Act, as a legal-control technological system, was predicted by its builders to have a finite lifespan. There would come a time when the system might not perform as useful a function as originally built.

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[63] Weil 1953.
[64] Joint Committee on Atomic Energy 1953, 7.
[65] U.S. Atomic Energy Commission 1946, 1.

"The effect of the use of atomic energy for civilian purposes upon the social, economic, and political structures of today cannot now be determined. It is a field in which unknown factors are involved. Therefore, any legislation will necessarily be subject to revision from time to time."[66]

The Atomic Energy Act of 1946 was born mortal. It had an inherent self-deconstructing life cycle. With human controlled nuclear fission occurring only four years previously, and nearly all nuclear research since that time focused on atomic weapons, the field of commercial nuclear technology was an unknown landscape. The Act was a broad and tall containing fence surrounding a field that was yet to be planted. Since the future of commercial nuclear energy systems was not known, the Act was over engineered to contain whatever technologies that came into being. It was expected that this legal structure would eventually become too stringent in its containment of nuclear knowledge and its application to practically progress civilian use of atomic energy.

"Sec. 7. (b) REPORT TO CONGRESS. — Whenever in its opinion any industrial, commercial, or other nonmilitary use of fissionable material or atomic energy has been sufficiently developed to be of practical value, the Commission shall prepare a report to the President stating all the facts with respect to such use, the Commission's estimate of the social, political, economic, and international effects of such use and the Commission's recommendations for necessary or desirable supplemental legislation."[67]

Paragraph 7(b) was a built-in indicator that would signal to the Atomic Energy Commission that the Atomic Energy Act of 1946 was possibly reaching the end of its functional life; where its protections could impede the U.S. advancing its development of *practical* commercial nuclear energy. 7(b) was also a mechanism to initiate the process

[66] U.S. Atomic Energy Commission 1946, 1.
[67] U.S. Atomic Energy Commission 1946, 10.

to life-cycle-replace (LCR) the Act with an updated legal-control system. Once it had determined the practicality of civilian atomic energy use, the AEC would create the 7(b) report as the initiating event of the Atomic Energy Act life-cycle process. Interestingly, the AEC's 1953 policy statement was not the initiating event, nor did it suggest that the report was forthcoming. Although it laid out the set of activities and conditions that would eventually require a replacement of the 1946 system it explicitly stated "that the time is not yet at hand for the report called for in Section 7 (b)."[68] The AEC considered that commercial nuclear energy was not yet known to be practical and it would take years of development to reach that point. The policy's implementation framework was meant to be legally allowed through interim legislation, thus giving the government and industry the opportunity to develop nuclear technologies and assess their feasibility for commercial nuclear power. The Act's 7 (b) indicator was flashing, but the AEC had discovered that the Act itself was restraining the process for its life-cycle-replacement. Less than a month after the AEC had issued the policy statement the Joint Committee on Atomic Energy held a remarkably lengthy fourteen-day hearing in Washington D.C. to hash out the way forward on private development of nuclear energy.

Joint Committee on Atomic Energy - Atomic Power Development and Private Enterprise - 83rd Congress - 1953

In the Summer of 1953, over sixteen days, a series of meetings were held in Washington D.C on commercial nuclear power development. This expansive hearing,

[68] Joint Committee on Atomic Energy 1953, 6.

by the Joint Committee on Atomic Energy (JCAE), was the culmination of over a half-decade of discussion and work by the U.S. government, their atomic contractors, and American industry on what it would require to move from a nationally controlled scientific and technological nuclear system to one that included private enterprise resources and investments. The JCAE brought into one room over fifty individuals, from nearly as many government and civilian agencies and companies, to give testimony on their views of the feasibility and practicality of reshaping the U.S. government's nuclear enterprise to fully incorporate U.S. private enterprise. The room was crowded with participants from the Atomic Energy Commission, the State Department, national laboratories, electric utilities, industrial companies, trade unions, and people with nuclear expertise. This diversity of participants also elicited a range of views and opinions of how the country should move forward and the level of effort involved, but all had an economic concern.

The JCAE's opening statement, concerning the reason for the meeting, portrayed the national pursuit of atomic energy in existential terms. They knowingly described it as the "atomic power race"; a conflict between the Western free world versus the Soviet East where it would be "suicidal folly" not to use atomic technology for the well being of the country and its allies.[69] To the Committee, the race was also one of not only technological power, but of conflict of fundamental cultures between those of the "Christian-Judaic-Moslem ethic…and the…atheistic materialists."[70]

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[69] Joint Committee on Atomic Energy 1953, 2.
[70] Joint Committee on Atomic Energy 1953, 2.

Congressman Cole's (Chairman of JCAE) opening remarks emphasized the non-military ethical goals of atomic energy where it was to be "harnessed to allay human wretchedness" and where the United States would "wish to share the benefits of peacetime atomic energy with all free peoples."[71] But Chairman Cole warned there would be a cost of both time and money to prevailing in the West versus East atomic race. He pointed out that there was general consensus that it was theoretically possible to produce commercial quantities of electricity with atomic energy, but he did not believe that "atomic power [would] be widely competitive in the United States with electricity generated from low-cost conventional fuels by the day after tomorrow."[72] With $12 billion previously invested by the United States in fundamental research and engineering, primarily for military weapons, Cole believed that the coming decade should be one of well-considered investment in atomic energy production development; consideration based upon experience because, as Cole pointed out, "We will not actually know how much atomic power costs until we produce it."[73]

Following Chairman Cole, Gordon Dean (Chairman of the AEC) assessed the current economic state of nuclear power technology as one where, "A nuclear plant built on the basis of today's technology could not compete with conventional power."[74] Dean identified the gap of technological knowledge as a consequence of the previous decade's research and engineering focus on the military applications of nuclear technology. The all-encompassing control mechanisms of the government's necessary

[71] Joint Committee on Atomic Energy 1953, 4.
[72] Joint Committee on Atomic Energy 1953, 3.
[73] Joint Committee on Atomic Energy 1953, 3.
[74] Joint Committee on Atomic Energy 1953, 5.

monopoly on nuclear weapons technology were now hindering commercial development of nuclear power. Gordon Dean summarized:

"It is the judgment of the Commission that now is the time to announce a positive policy designed to recognize the development of economic nuclear power as a national objective. An important element of this policy is to promote and encourage free competition and private investment in the development work, while at the same time accepting on the part of Government certain responsibilities for furthering technical progress in this field to provide a necessary basis for such development."[75]

"While we conclude that atomic power has not yet been developed to the point of economic use, and that the time is not yet at hand for the report called for in section 7 (b) of the Atomic Energy Act, we do believe it is imperative that we create a favorable atmosphere which will hasten that day."[76]

Dean's Commission had concluded "that atomic power [had] not yet been developed to the point of economic use" and it was now advocating for a trusted partnership between the U.S. government and American private industry to practically develop economically feasible commercial nuclear power in a reasonable amount of time; the Cold War was heating up.[77] For added emphasis (the policy had already been presented to the Committee the previous month) Dean read into the hearing record the AEC's policy on nuclear power development. This was the initial framing of what would eventually become the Atomic Energy Act of 1954; the act that would allow nuclear knowledge and technologies to become components of a commercial nuclear power industry.

Dr. Lawrence Hafstad, Director of the Reactor Division of the AEC, explained the high level fundamentals of a nuclear reactor as a heat source in an electrical power

[75] Joint Committee on Atomic Energy 1953, 6.
[76] Joint Committee on Atomic Energy 1953, 6.
[77] Joint Committee on Atomic Energy 1953, 6.

plant using a chart schematic that would not look out of place today.[78] Hafstad then presented an illustration that showed a side-by-side comparison of conventional and nuclear power plant costs per watt of electricity. Without operational experience, and with the anticipation of encountering technical unknowns, the costs of construction and operation of a nuclear plant was broadly estimated to produce electricity at $1000 per kilowatt while conventional coal fired plants were at $150 per kilowatt. Hafstad called this cost of reactor produced power, "A megabuck for a megawatt" and said for nuclear to even begin to become economically competitive with conventional its cost would need to drop below $200 per kilowatt.[79]

W.L. Davidson, Director, AEC's Office of Industrial Development, spoke from his experience as the head of a 14 month old organization setup by the AEC to "foster wider industrial participation…and the development…of a more normal competitive approach to the problems and potentials of the atomic-energy business."[80] The AEC was actively beginning to ready itself for the dismantlement of the Atomic Energy Act of 1946 and to engage on profitable economic designs of a commercial nuclear power business model. Davidson detailed his office's engagement with 365 industrial groups, big and small, throughout the country and summarized their "interests and intents"[81] in several points to include American industry's interest in using nuclear fuel to economically power commercial electrical power plants if enabled by appropriate legislation; new laws that would allow for private ownership of patent rights on nuclear

[78] Joint Committee on Atomic Energy 1953, 16.
[79] Joint Committee on Atomic Energy 1953, 19.
[80] Joint Committee on Atomic Energy 1953, 27.
[81] Joint Committee on Atomic Energy 1953, 27.

technologies; and new laws that would solidify and make legible the "nebulous state of knowledge possessed by a majority of industry."[82] Davidson concluded that, at the present time even with legislative changes, private enterprise would not be willing to fund the construction of a nuclear power reactor without a "great percentage of Government funds."[83]

The U.S. State Department weighed in with, unsurprisingly, the view that effective international relations were vitally important to the country and the domestic nuclear power project was critical to that effectiveness. The U.S. had to show the world it was leading the way, ahead of the Soviet Union, in the peaceful advancement of nuclear technologies. To that end, Under Secretary of State Walter Smith told the Committee that "atomic energy should become integrated into the national economy as rapidly as, and to the extent that, security considerations permit."[84]

American private enterprise told the government, straightforwardly and with few reservations, that if they got out of the way industry would eagerly lead development of commercial atomic energy in the United States. Detroit Edison and Dow Chemical led a group of twenty-six companies composed of electric power utilities, manufacturing, chemical and engineering organizations that advocated "private competitive industry development of atomic energy for peacetime purposes."[85] The group was keen to invest their own money to further their business enterprise:

[82] Joint Committee on Atomic Energy 1953, 29.
[83] Joint Committee on Atomic Energy 1953, 29.
[84] Joint Committee on Atomic Energy 1953, 63.
[85] Joint Committee on Atomic Energy 1953, 135.

"It is important to stress the reasons for our intense interest: (1) Heat energy is a major cost item in our businesses, and a more economic source of heat energy means greater economy in the production of products for general public use; and (2) these companies believe that this development can and should be carried forward by competitive enterprise, with its own resources, subject to reasonable governmental regulation for purposes of national security and safety."[86]

To carry this out, their ambitions were aggressive and they stated, "the group intends, with private funds, to design, construct, test, and operate a full-sized breeder reactor."[87] The test reactor would be used determine the economic practicality of commercial nuclear power production, but financing plans would only be developed by industry if the Atomic Energy Act of 1946 was modified to allow full participation by private enterprise.

Dr. Chauncey Starr, the director of atomic research at North American Aviation, the prime nuclear contractor with the AEC, testified that atomic power needed to be providing substantial electricity to the country in the next twenty-five years due to what was foreseen as eventual depletion of fossil fuels. In other words, commercial atomic power had to become both technically and economically viable over the next two to three decades. In the near term, Starr argued, significant investment was needed by both the government and private industry to develop engineering knowledge and operational experience with what he called "pilot-plant-size machines."[88] Without that earned experienced Starr estimated that with the current state of nuclear knowledge an atomic power plant built today would produce electricity at twice the cost of a

[86] Joint Committee on Atomic Energy 1953, 136.
[87] Joint Committee on Atomic Energy 1953, 138.
[88] Joint Committee on Atomic Energy 1953, 253.

conventional plant. In Starr's view the efforts toward system development would be an investment of time and money that the government would need to share with industry:

> "My own feeling is simply that the Government should pay for the manufacture of knowledge, but should not subsidize the manufacture of power. We feel, as I indicated in my statement, that Government support in the manufacture of knowledge is a justified thing."[89]

Perhaps there was no other person, testifying at the hearings, with more hands-on experience with atomic technology than Westinghouse's Atomic Power Division's manager Charles Weaver. His experience gave him a valuable view of how the Atomic Energy Act of 1946 would actually affect the development of nuclear technology at the practical level. With Westinghouse as the AEC's prime nuclear contractor, Weaver oversaw and managed all of the nuclear projects. He was responsible for the design and construction of a nuclear reactor for Admiral Hyman Rickover's nuclear submarine Nautilus; the submarine thermal reactor or STR. Just over three months prior to his appearance before the Committee his team had taken the land-based prototype of the Nautilus' reactor to criticality at the U.S. state of Idaho test site. That test reactor had even produced a nominal amount of electricity so, at least at a small scale, Weaver had demonstrated that a nuclear power plant was technically feasible. Weaver described Westinghouse as a designer, builder and seller of "atomic machinery"[90] and therefore the Atomic Energy Act of 1946 restrictions on the ownership of atomic material was not of direct concern to Westinghouse. It was the electric utilities who would operate

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[89] Joint Committee on Atomic Energy 1953, 257.
[90] Joint Committee on Atomic Energy 1953, 280.

Westinghouse's atomic machinery fueled with fissionable material who would be directly constrained by the Act.

Weaver was primarily concerned that the Energy Act constraints would slow or even halt the momentum of research, development and engineering of nuclear technologies. He emphasized that the trained and experienced cadre of atomic scientists, engineers, technicians, and established facilities, were resources that could not be replaced if development was allowed to slow and dissipate due to lack of political will to proceed and loss of both government and private funding for joint activities. To keep the momentum Weaver argued that it was time to amend the law so research and practical construction could progress without impediment. That change was key for knowledge and nuclear system development as he candidly told the Committee, "In the atomic power field…there are still no experts; there are only varying degrees of ignorance."[91] To move ahead, Weaver recommended the building of a full scale plant since he questioned what could be learned from smaller pilot plants since the objective was to prove that large plant could be effectively operated and produce electricity at a large scale. There was much to be learned as Weaver explained, "We do not know, and no one knows, whether the first plant could produce competitively with ordinary plants."[92]

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[91] Joint Committee on Atomic Energy 1953, 284.
[92] Joint Committee on Atomic Energy 1953, 283.

Building Atoms for National Peaceful Power

For the United States, commercial nuclear power became a Cold War strategic imperative as it positioned itself against the Soviet Union and postured on the world stage to persuade countries to align themselves with the United States and its modern technologies. Nuclear power was to showcase to "the world that the industrial vigor of America continues to lead the way to a decent standard of living…for [America] and for [its] friends."[93] The U.S. was realizing that while its numbers of nuclear weapons, and intercontinental bombers, were of strategic military importance to threaten the Soviet Union, it was nuclear power and international engagement, that was also of strategic political importance.

Eisenhower - 04-08 December 1953 - Bermuda Meeting with Churchill and Laniel

On the fifth of March 1953, four months after the United States had exploded the first hydrogen bomb, the Soviet leader Joseph Stalin died. There were four months of fighting remaining in the Korean War. Beneath the specter of a thermonuclear cloud, Cold War maneuvering between the West and the Soviets was escalating even as their proxy shooting war was ending. Moreover, maneuvering between the Western allies themselves was increasing amid their uncertainties regarding the new Soviet leadership and how the West should mutually configure and posture itself in response. This

[93] Joint Committee on Atomic Energy 1953, 2.

situation brought the ‘Big Three’ western powers, the United States, Great Britain and France, together in a joint meeting at the end of 1953. American President Dwight Eisenhower, British Prime Minister Winston Churchill and French Prime Minister Joseph Laniel held a conference from 04 to 08 December 1953 on the British territory of Bermuda. The three leaders’ agenda going into the conference was to: assess the posture of the new Soviet leadership and how the U.S., Britain and France would affect some type of cooperation with the Soviets and; discuss the ongoing debate and process of approval of the European Defense Community (EDC) treaty, the stability of the new and supposedly holding Korean armistice, and France’s situation in Indochina.[94] These international concerns were overshadowed by the sociopolitical thermonuclear cloud (and actual nuclear clouds in the South Pacific and central Asia) that had been expanded further with the Soviet’s test of their first hydrogen bomb in August 1953.[95] Churchill prodded Eisenhower to reestablish atomic information sharing and even cooperation in atomic warfare planning with Britain. This included the U.S. providing information on Soviet targets and use of American atomic weapons with Royal Air Force bomber aircraft. Churchill specifically asked for the weight and dimensions of American bombs in order to plan British bomber design.[96] Eisenhower listened to Churchill with appreciation and told him that the U.S. was working to amend the McMahon Act (the Atomic Energy Act of 1946) to allow the legal exchange of nuclear information.[97] This comment about loosening U.S. law that contained nuclear knowledge was further

[94] Young 1986.
[95] Mazuzan and Walker 1985.
[96] Bermuda Meeting 04 December 1953.
[97] Bermuda Meeting 04 December 1953.

applicable to what he had presented to Churchill and Laniel the previous day in Bermuda; to share the atom with all nations.

Eisenhower proposed a different "approach to co-operation with Russia: an attempt to bring about the international control of atomic energy."[98] Still beneath the expanding nuclear weapons shadow, Eisenhower sought to plan the construction of a nuclear foundation to be built by the international community to support peaceful uses of the atom. He presented Churchill and Laniel with his thoughts concerning his soon to be given speech before the United Nations General Assembly where, of course, the Soviets would be in attendance with the world's nations. His intent was to begin to counterbalance the focus of the destructive powers of the atom and to build a community that promoted nuclear technology of energy production, medicine, agriculture, and other peaceful purposes. Not only would knowledge of nuclear technology be shared by the United States with other nations, but fissile material would be literally shared by nations through a United Nations' controlled and managed nuclear "bank" containing atomic deposits by contributing nations: the U.S., the Soviet Union and the U.K. Other nations would be able to withdraw nuclear material so as to "be made available to the scientists of the world to use for practical purposes."[99] Eisenhower wished to show the world that while the potential for nuclear destruction still loomed the U.S. and other nuclear nations could put forth actions to tangibly refashion nuclear technology. With effort it could be reshaped from being a technology of just

[98] Young 1986, 905.
[99] Bermuda Meeting 04 December 1953, 3.

destruction to a technology of civil advancement throughout the world.[100] Eisenhower also hoped that his promotion of the peaceful side of the atom would encourage private conversations with the Soviets and "bring disarmament a little closer."[101] It would also encourage nations to recognize the goodwill of the United States and to align more closely with the West rather than the Soviets. With Churchill's and Laniel's endorsement, Eisenhower left Bermuda on the 8th of December and addressed the UN General Assembly that afternoon in New York.

Eisenhower - 08 December 1953 - Atoms for Peace at UN

With the United Nations' global emblem, surrounded by olive branches symbolizing peace, looming behind him, Eisenhower stood at the podium and addressed the U.N. General Assembly on Tuesday afternoon of the 8th of December 1953.[102] He talked bluntly of atomic warfare and of the atomic age and the need for the citizens of the world to understand the extent of its development. To show the United States' position in the world atomic order, Eisenhower spoke of how the U.S. had conducted 44 atomic test explosions, (but without mention of Hiroshima and Nagasaki), described its large stockpile of weapons, and the ability of its military to use those weapons. He emphasized how the secret of the atomic bomb was also known by the Soviet Union and the secret of nuclear destruction would eventually be known by others. With the specter of atomic warfare annihilating civilization, Eisenhower turned

[100] Bermuda Meeting 04 December 1953.
[101] Bermuda Meeting 04 December 1953, 4.
[102] Mazuzan and Walker 1985.

his speech toward the prospect of shifting resources and knowledge from destructive weapons to atomic energy as a means of peaceful benefit for all.

> "The United States knows that peaceful power from atomic energy is no dream of the future. That capability, already proved, is here — now — today. Who can doubt, if the entire body of the world's scientists and engineers had adequate amounts of fissionable material with which to test and develop their ideas, that this capability would rapidly be transformed into universal, efficient, and economic usage."[103]

As he had described in Bermuda, Eisenhower proposed the creation of an International Atomic Energy Agency, under the United Nations, that would gather, control and distribute stockpiles of uranium jointly contributed by donor nations. The agency would be responsible to "devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind."[104] Eisenhower's top secret classified talk with Churchill and Laniel, just four days before, had now become an open talk before the world. It extolled the potential benefits of the atom to the international community and was also a challenging diplomatic invitation to the Soviets to work with the West through the United Nations. The peaceful challenge carried forward Eisenhower's National Security Council's April 1953 policy that stated, "Atomic energy, which has become the foremost symbol of man's inventive capacities, can also become the symbol of a strong but peaceful and purposeful America."[105] However, Eisenhower had presented a plan, but as he spoke on that December day in 1953, he did not have the ability to implement the plan. His proposed peaceful nuclear Cold War

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[103] Eisenhower 1953, 7.
[104] Eisenhower 1953, 8.
[105] U.S. National Security Council 1953, 47.

weapon was contained by the Atomic Energy Act of 1946 and he could not deploy the weapon. To be credible, Eisenhower would have to push American lawmakers to amend the Act to allow the sharing of nuclear knowledge and material.

Eisenhower - 17 February 1954 - Message to Congress

The push came just over two months later on 17 February 1954, and three weeks after the launching of the world's first nuclear powered submarine; Admiral Hyman Rickover's U.S.S. Nautilus.[106] President Eisenhower, in a special message to Congress, recommended that the Atomic Energy Act of 1946 be amended by the law makers to lessen the statutory restrictions on sharing of scientific and engineering information on atomic energy.[107] The President argued that the 1946 law's focus on protecting atomic weapon knowledge was now too restrictive for advancing atomic energy, "These restrictions impede the proper exploitation of nuclear energy for the benefit of the American people and of our friends throughout the free world."[108] Eisenhower recommended changes that would allow sharing of atomic information with other nations, that the security classification of "restricted data" be revised to allow more efficient and less costly dissemination of information with the Department of Defense (DoD) and industry, and to "permit private manufacture, ownership and operation of atomic reactors and related activities."[109] The President was deftly backing his U.N.

[106] Duncan 1990.
[107] Mazuzan and Walker 1985.
[108] Eisenhower 1954, 1.
[109] Eisenhower 1954, 1.

address with the simultaneous launch of the Nautilus and his move to change American nuclear law. Eisenhower would soon have an atomic powered warship capable of lurking beneath the polar icecap at the backdoor of the Soviet Union and a legal and regulatory nuclear infrastructure capable of supporting peaceful uses of the atom. Both capabilities were Cold War weapons with one a weapon to win military deterrence and the other a weapon in the form of an "international propaganda campaign" targeted to win "hearts and minds."[110] With the bomb already in place and its development proceeding rapidly, Eisenhower was pushing Congress, the AEC and American industry to construct the legal and technical infrastructure to build the weapon of nuclear power; even if they had yet to fully determine the practicality of commercial nuclear power systems.

Atomic Energy Act - 1954 (The Curtain goes up on the Second Act…)

With the Atomic Energy Act of 1954, the United States moved from the 1946 Act's structure of a government owned and controlled nuclear research and development (R&D) program to a program radically changed to bring in the nearly independent participation of private industry. The program included government licensing and regulation of commercial reactors and the use of fissionable material, furthermore, and most significantly for Cold War power posturing, it allowed the U.S. to develop and share nuclear technologies internationally with current and potential allies. After eight years of national focus on weapons R&D and a government monopoly on all things

[110] Wolfe 2018, Introduction. Kindle.

nuclear, the United States had assessed that it had to continue development of its atomic energy law. The 1946 law was explicit in stating that the effect of civilian atomic energy was then unknown and therefore the 1946 Act would be "subject to revision from time to time."[111] Now was the time for the U.S. to expand its capabilities to further develop and implement nuclear technologies in a world where the technology of the atom was not only seen as a destroyer of worlds but as a builder of world societies.

While the 1946 Act promoted private research, through government contracts, to advance *scientific* progress, the new Act pushed research and development "to encourage maximum scientific and *industrial* progress"[112] [emphasis added]. Using identical language, the Act also provided for the declassification, where possible, of Restricted Data, "to encourage…scientific and industrial progress."[113] In two sentences the Atomic Energy Act of 1954 had breached the government containment of nuclear technology and knowledge. Additionally, the Act unequivocally promoted the "widespread…utilization of atomic energy for peaceful purposes…to the maximum extent."[114] It further encouraged wide "international cooperation…to make available…the benefits of peaceful applications of atomic energy."[115] While the government monopoly on nuclear knowledge and its use was broken, the legal ownership of nuclear material remained with the Atomic Energy Commission. It was another decade before the AEC relinquished its sole ownership monopoly.[116]

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[111] U.S. Atomic Energy Commission 1946, 1.
[112] U.S. Atomic Energy Commission 1954, 922.
[113] U.S. Atomic Energy Commission 1954, 922.
[114] U.S. Atomic Energy Commission 1954, 922.
[115] U.S. Atomic Energy Commission 1954, 922.
[116] U.S. Nuclear Regulatory Commission 2013b.

Eisenhower's international and domestic peaceful atom strategy was now at least legally feasible and U.S. industry could potentially move forward to construct a commercial nuclear industrial environment; economically practical or not. A significant consideration for industry was the risk of economic liability in the event of catastrophic reactor failure that caused widespread nuclear contamination and hazarded the public. That was a financial liability risk that nuclear power producers could not readily accept. Further revision of the Atomic Energy Act was on the not so distant horizon.

The Atomic Energy Act of 1954 allowed private companies to legally pursue independent development of nuclear knowledge and technologies and, at least theoretically, to make money with commercial nuclear power without the all-encompassing control of the government. When the Act became law in August 1954, the business practicalities of legal nuclear development and operations still remained in question. A significant practical business concern was a company's financial liability for a nuclear accident. At the time, the scope of indemnification for conventional industrial accidents was not designed to cover what would be estimated as the worst-case consequences of a nuclear industrial accident. Insurance of sufficient coverage did not exist. Worst case was considered, by the nuclear experts (as we will see), to be the failure of the reactor vessel, failure of the containment structure (typically by explosion) and the spread of radioactive contamination over large areas (as affected by the weather and other variables) affecting large populations, perhaps permanently.[117] It was clear that no single company, or for that matter the industry as a whole, could

[117] U.S. Atomic Energy Commission 1957.

survive that type of catastrophe. Nonetheless, the newly born nuclear industry initiated development efforts and began to move to engineer and build nuclear power plants; it would be several years before there would be a practical and a critical need of insurance for companies' reactors.

Price-Anderson Act - 02 September 1957 (Risk of Lock, Stock and Barrel)

By May of 1957 contracts had been awarded for the building of six nuclear power plants in the United States. The Shippingport Atomic Power Station in Pennsylvania was only seven months from going critical, and in Illinois the Dresden Nuclear Power Station, Unit 1 was well under construction by the General Electric Company (GE).[118] In March of 1957, at hearings before the Joint Committee concerning insurance coverage under the Price-Anderson Act, the manager of the Atomic Products Division of GE, Francis K. McCune "thought such coverage would probably be necessary if the goal of widespread atomic industrial progress was to be achieved."[119] McCune further emphasized to the Joint Committee that if the Congress did not immediately implement a means to insure nuclear power plants against catastrophic accidents then GE would stop work on the Dresden power plant; he additionally advised that other companies would most likely choose not to move forward with their plant construction projects.[120] The government and the commercial nuclear industry had pressed on with building a suitable environment to support Eisenhower's vision for a peaceful Atom, but progress

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[118] Rolph 1979.
[119] Mazuzan and Walker 1985, 94.
[120] Mazuzan and Walker 1985.

was only sustainable as long as reactors were not operating; as long as there was not a sustained fission reaction. Time was critical for the government to reconfigure the Atomic Energy Act of 1954 with national protections against nuclear failures.

Two members of the Joint Committee on Atomic Energy took the lead to fit a government funded financial shield to the Atomic Energy Act that would protect private industry from nuclear accidents. Congressman Charles Price (Democrat, Illinois) and Senator Clinton Anderson (Democrat, New Mexico) jointly sponsored the legislation that bears their name to amend the Atomic Energy Act of 1954.[121] The Price-Anderson Act of 1957, stated that "to encourage the development of the atomic energy industry…the United States may make funds available for a portion of the damages suffered by the public from nuclear incidents, and may limit the liability of those persons liable for such losses."[122] Beyond the required, private liability insurance coverage, the federal government would ensure indemnification of electric utility companies in the event of catastrophic failure of their nuclear reactors for up to $500,000,000 for each incident.[123] With the construction of this subsidy the government had funded the nuclear industry's risk of the unknown as they engineered and built the country's nuclear power infrastructure.

[121] U.S. Congress 1957.
[122] U.S. Congress 1957, 576.
[123] U.S. Congress 1957.

WASH-740 - 1957

Even before the first American nuclear power plant was operational the AEC's assessment of future reactor safety and the risk of failure had introduced the thinking that plants would be too safe to fail; a framing that would generally be in the minds of the AEC, the nuclear industry, and the public for the next two decades. In July 1956, as the construction of the Shippingport Atomic Power Station was in progress, the Joint Committee on Atomic Energy asked the AEC to execute a study that assessed the "possible consequences in terms of injury to persons and the damage to property, if certain hypothetical major accidents should occur in a typical large nuclear power reactor."[124] The study, titled the "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants" with the AEC designation of WASH-740, was carried out by the engineering and scientific staff of the Brookhaven National Laboratory at Upton, New York.[125]

In the forward of the study, delivered to the Joint Committee in March of 1957, acting AEC chairman Harold Vance good naturedly said, "We are happy to report that the experts all agree that the chances that major accidents might occur are exceedingly small."[126] This was apparently meant to be reassuring since Part I of the report was titled, "The Probability of Catastrophic Reactor Accidents."[127] Vance went on to explain that the motivation of the report was that, "the experts and the Congress and the public

[124] U.S. Atomic Energy Commission 1957, vii.
[125] U.S. Atomic Energy Commission 1957, Cover.
[126] U.S. Atomic Energy Commission 1957, vii.
[127] U.S. Atomic Energy Commission 1957, 3.

and the Commission have all been concerned with the causes of and the possible magnitude of damage from reactor accidents and with means of prevention."[128] The concern was even rather dramatic for some due to the, unsurprising, association of nuclear technology with weapons. The report, in its very first paragraph explicitly addressed this coupling:

> It might be supposed because the essential fuel in a nuclear power reactor is the same as that in atomic bombs that gross malfunctioning in power reactors could possibly lead to a devastating explosion such as those produces by A-bombs. Such is not the case. Under no conceivable circumstances can accidental nuclear explosions in power reactors cause significant direct public damage beyond the boundaries of the exclusion areas around such installations.[129]

Catastrophe was not to be in the form of a mushroom cloud explosion. If a reactor did explode, the direct damage from the catastrophe would be limited (although perhaps not entirely) to the area immediately around the reactor installation. So, the hazards of a reactor *explosion* were localized to the people working at the plant. If you were away from the blast you should be fine. The report then presented a caveat:

> There is however, another hazard to the general public which could cause extensive loss of life and damage to property. This is the possibility of radiation exposure and contamination if the fission products stored up in the reactor should be released.[130]

The government was making clear that an accident involving a nuclear power reactor was *not the same* as other industrial accidents, such as that might occur at a coal or oil-

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[128] U.S. Atomic Energy Commission 1957, vii.
[129] U.S. Atomic Energy Commission 1957, 1.
[130] U.S. Atomic Energy Commission 1957, 1.

fired power plant. A nuclear accident “conceivably could occur and that a serious threat to the health and safety of people over large areas could ensue.”[131] The Brookhaven experts estimated the likelihood of the catastrophic failure of a large nuclear reactor, that harmed the public, ”ranged from a chance of one in 100,000 to one in a billion per year for each reactor.”[132] In other words a 0.00001 chance of a catastrophic failure of a reactor operating for one year or, at very much the extreme, a 0.000000001 chance of reactor catastrophe in one year.

These exceedingly small probabilities and their large, four order of magnitude, range were due to the fact that the nuclear experts were being asked a question by the AEC that they were hard pressed to provide a reasonable answer; some were reluctant to give a quantifiable number. No one had experience with accidents involving large, operational reactors; there simply had not been significant accidents with those systems. While accidents with experimental reactors had occurred, the nuclear experts argued that this information was not useful to predict the probability and consequences of accidents involving large power plants. Some in the queried group of experts, with their current experience and knowledge of reactor accidents, thought that a “numerical estimate of quantity so vague and uncertain [as to] have no meaning.”[133] Other experts in the group, while also extremely uncertain, did provide the numbers that spanned the immense distance from 100 thousand to 1 billion. Further, the experts rather reluctantly predicted that the consequences of one of these highly unlikely failures would kill

[131] U.S. Atomic Energy Commission 1957, 1; Wellock 2017.
[132] U.S. Atomic Energy Commission 1957, viii.
[133] U.S. Atomic Energy Commission 1957, viii.

anywhere from zero to 3,400 people with about 43,000 injured. The range of costs of an accident was also laid out by the Brookhaven experts as extremely broad from $500,000 to $7 billion. This presented another four order of magnitude range of uncertainty with most theoretical accidents occurring somewhere in the middle and costing several hundred million dollars.[134] Absent firsthand experience with accidents, and with worst case reactor failures predicted to produce supremely catastrophic consequences, why were the Brookhaven experts so liberal with their reactor accident probability estimates?

The no-failure experience they *did* have with reactors, since the first went critical in 1942 , certainly helped to construct their probability views, but it was primarily due to their belief that the government and the nascent nuclear industry *themselves* recognized that a nuclear system differed from other industrial technologies. The AEC argued that, unlike with conventional systems, "the potential hazard of this new industry has been recognized in advance…and brought under a strict system of safety control before the occurrence of incidents."[135] Here they were quite explicit in claiming that the identification of potential nuclear system failure was legible and could be preventively engaged with. Why was that? Again, the AEC reasoned that the uniqueness of the nuclear technology, and the catastrophic consequences of its failure, had driven, and would continue to drive, governmental regulatory oversight, engineering design, operational methods, and the motivation of "able and energetic men"[136] to high levels of

[134] U.S. Atomic Energy Commission 1957.
[135] U.S. Atomic Energy Commission 1957, ix.
[136] U.S. Atomic Energy Commission 1957, ix.

effectiveness and professional competence. There was confidence that, by its very nature, the nuclear system would construct itself as a safe and reliable technology where, as the AEC put it, "the "conceivable" catastrophe shall never happen."[137] The confidence of never was pervasive for the next two decades until the early morning hours of 28 March 1979 on an island in the middle of the Susquehanna River.

[137] U.S. Atomic Energy Commission 1957, ix.

Chapter 3
Three Mile Island Unit 2

Yet, by the recent attempt in a series of articles to ring an alarm 'of nuke disaster,' the York Daily Record has abandoned both that principle and the paper's journalistic obligation under the First Amendment... . We submit that this campaign in the Record is tantamount to yelling 'fire' in a crowded theater when there is no fire. We are certain that the citizens of York County will seek out the facts and not accept fantasy.[1]

- Walter Creitz, President of Met-Ed.

On 26 March 1979, a mere two days before the inconceivable became a reality, the local residents around the Three Mile Island nuclear plant read, in the York Daily Record, the critical response to the paper's reporting on problems at the plant. Walter Creitz of Metropolitan Edison (Met-Ed), the electric utility that operated TMI-2, characterized any potential accident as "fantasy." His view was fully consistent with the WASH-740 report, published twenty-two years, to the month, before; the probability of a conceivable reactor accident was so fantastically remote that it was essentially not considered possible.

In this chapter I will describe technical details of the TMI-2 plant, what failed in the accident, and how the plant failed. Most extensively, I will examine the actions that the regulatory and industry components, of the commercial nuclear power system, took in

[1] Creitz 1979.

the aftermath of the accident. I will consider their investigative reports and subsequent actions to show how, if slowly, the inconceivable accident, one found to be initiated by maintenance itself, came to be known and understood by the nuclear community as conceivable.

The Nuclear Power Plant System

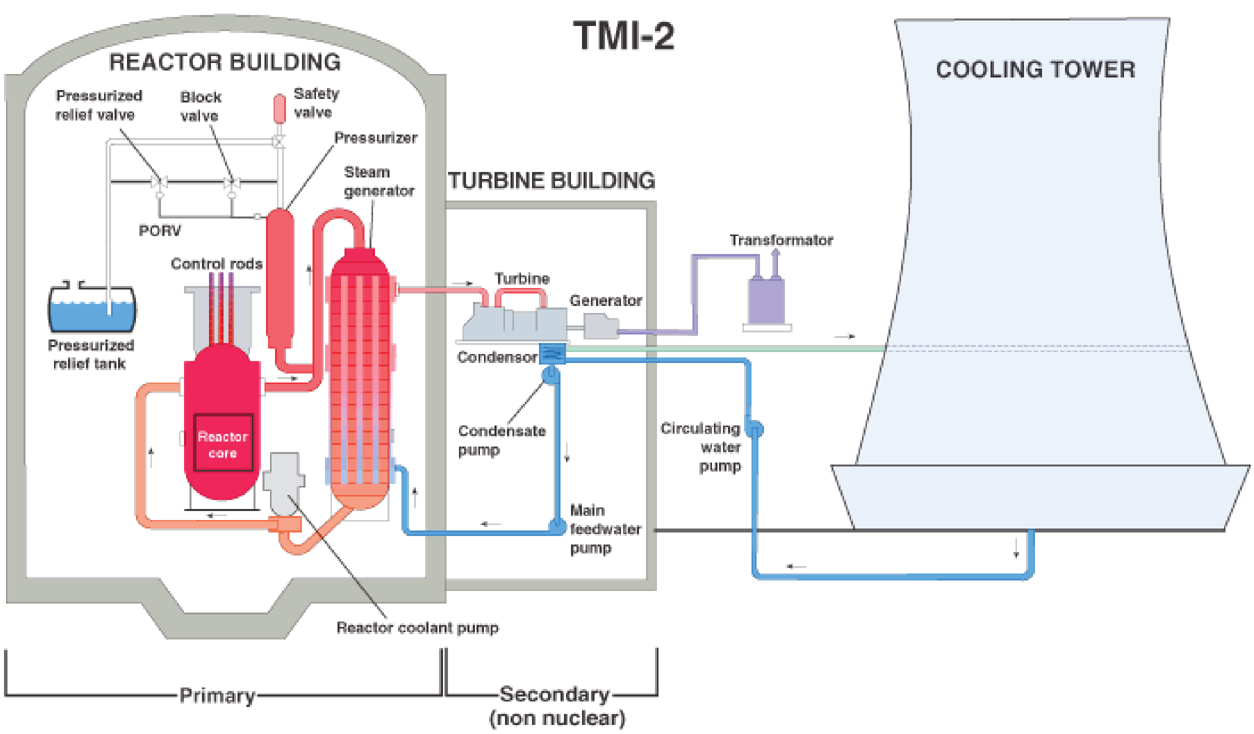
To help the reader gain at least a high-level understanding of the reactor unit and the conceivability of the accident I will briefly describe the workings of the Three Mile Island power plant relevant to the accident events. My intent is not to overwhelm with technical details, but to provide an appreciation for the plant's complexity and the interactions of its systems and components.

The TMI-2 reactor unit was a pressurized water reactor (PWR) made by the Babcock and Wilcox Company (B&W) of Barberton Ohio [see Figure 1 for a TMI-2 plant schematic]. It was licensed by the NRC on 08 February 1978 and first went safely critical on, ironically, 28 March 1978, precisely one year before the accident. Unit 2 was connected to the Pennsylvania power grid on 30 December 1978 and began to generate electricity.[2]

As its name describes, a PWR keeps its primary cooling water under high pressure (about 2,200 psi) so the water can be heated to high temperature (approx. 575 degrees Fahrenheit) and not boil. The primary coolant system's (or loop's) pressure is regulated by a large cylindrical device called a pressurizer. It contains a volume of steam and

[2] Walker 2004.

water that can be adjusted by the reactor operators to maintain desired pressure in the system. The pressurizer also has a pressure relief valve, known as the pilot-operated-relief valve or PORV, that will automatically open to relieve dangerous pressure and then automatically close when the system returns to normal. The high temperature water flows in a loop from the reactor vessel and pressurizer to steam generators where it indirectly heats a secondary water loop, or feedwater loop. Within the steam generator the feedwater is converted to dry, high temperature, steam that is piped out of the reactor containment building to drive a turbine that spins an electricity producing generator. Systems outside containment, such as the turbines, generators and much of the feedwater components, are collectively known as balance-of-plant (BOP). See Figure 1:[3]



[3] U.S. Nuclear Regulatory Commission 2018.

Once the steam exits the turbine it is cooled and condensed back into feedwater by the circulating water cooling loop. The circulating water itself is cooled in the iconic looking cooling towers that loom above the plant. Before the feedwater returns to the steam generators it is demineralized in devices known as condensate polishers (not shown in Figure 1, but in the area of the condensor and the condensate pump). The condensate polisher is part of the overall feedwater system and its function is to remove dissolved, contaminating minerals from the water so they do not clog and damage piping, pumps, valves, turbines, steam generators and other components of the feedwater system. Once treated by the polishers the feedwater is pumped back into the steam generators to begin the heating and steam cycle again.[4] It was a functional discrepancy with the BOP polishers and an associated corrective maintenance task that became the initiating event of the TMI-2 accident.

The Inconceivable

During the early morning of 28 March 1979, just after 4:00am, a plant maintenance team was working on condensate polishers in the turbine building adjacent to the massive steel and concrete reactor containment structure. The polishers operate like a home water-softener, but at an industrial scale. They contain resin beads that ionically remove contaminating minerals from feedwater that flows to the reactor for cooling. If, as discussed, left untreated mineral deposits would eventually clog the feedwater

[4] Garwin and Charpak 2001.

system of pipes and valves. The plant had been having problems with the polishers reducing the flow of feedwater. After periods of use the resin beads can become impacted and require maintenance that injects water and air into the polishers to unclog the beads for the proper flow of feedwater. The water or air that was being used by the maintenance team that morning to unclog the polisher resin beads were inadvertently forced into the instrument-air (IA) system which caused all of the inlet and outlet polisher valves to close uncommanded. (The IA is a specialized pneumatic system that provides dry and conditioned air to control the positioning of pneumatically actuated valves). With all of the polisher valves closed the flow of feedwater is stopped to the steam generators which in turn stops the main feed to the turbines. Without a water feed the turbines tripped, or shutdown, as designed. The primary coolant immediately begins to heat since the turbines are no longer removing heat. As the coolant heats it expands and increases pressure in the primary loop which causes the PORV on the top of the pressurizer to automatically open to relieve the pressure; again, as designed. When the coolant pressure drops to an acceptable level the PORV would close as designed; the TMI-2 pressurizer PORV did not close. The massive coolant system, engineered to remove tremendous heat from the reactor core, was now uncontrollably pouring coolant out on to the floor of the containment structure.

The stuck open PORV led to a Loss-Of-Coolant-Accident (LOCA) as steam and coolant vented through the valve. The reactor operators were unable to rapidly understand and properly respond to the malfunction due to system deficiencies in plant design, and their own knowledge and training. Eventually, before the position of the faulty PORV was recognized and the valve closed by the operators, the coolant level in the reactor vessel dropped and partially uncovered the nuclear fuel rod assemblies. Without cooling water, the fuel rods "failed" or, to be more commonly descriptive, melted. Ultimately, the operators halted and contained the core destruction, but there were fears of a hydrogen explosion and some quantity of radioactive gasses were released into the atmosphere. The reactor was destroyed and so was public confidence in government and the nuclear industry. A maintenance activity (ironically), a stuck valve, ineffective system indicators, and inability to understand the condition of the reactor had destroyed the confidence in never. Power plants were not too safe to fail. The inconceivable had become recognizably and dramatically conceivable.

Three Mile Island Unit 2 Accident - Aftermath and Assessments

Three Mile Island put commercial nuclear power front and center before everyone. It was extensively and dramatically covered by the media not only as headline news as the accident transpired, but in its aftermath. Time Magazine's 09 April 1979 cover photograph showed dark and looming TMI cooling towers with the words "Nuclear Nightmare" in red superimposed.[5] Life Magazine's May 1979 issue featured an almost identical photograph of the towers on its cover with the less dramatic title, "Judgement Day for Nuclear Power," but with the telling questions: "Is public confidence gone forever?" and, "Are the newest plants safe to open?"[6] The effectiveness of nuclear

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[5] Time Magazine 1979.
[6] Life Magazine 1979.

plant operational safety, reliability, and regulation were under existential scrutiny; failure of a BOP water-softening system had been fatal for one nuclear reactor and now there was the specter that this failure could be fatal for the entire nuclear industry. As the American public looked warily at iconic cooling towers just beyond their backyard fences, and at the glossy magazine images on their coffee tables, the American government and nuclear industry were heavily engaged in generating numerous analyses and reports on what happened, why it happened, and the planned way-ahead for the life of commercial nuclear power.

The government and industry immediately began investigations that examined and reported deficiencies in regulatory mechanisms and oversight, plant design and engineering, operator training and human factors, and emergency response and public engagement. Interestingly, maintenance was discussed within the reports, but the type of attention it received was not what we might have expected given the role a failed condensate polisher system and stuck PORV played in the accident.

Within weeks of the TMI-2 accident several government and industry technical groups began investigating the events comprising and surrounding the accident. The investigations examined and reported deficiencies in regulatory mechanisms and oversight, plant design and engineering, operator training and human factors, and emergency response and public engagement. The investigative groups were from the NRC itself, a third party contracted by the NRC, a Presidential commission, and the industry's Electric Power Research Institute (EPRI). An NRC task force nearly immediately published a lessons learned report in July 1979.[7] The very next month the NRC's Office of Investigation and Enforcement also published a report as NUREG-0600.[8] The investigation was not only for the NRC to perform. U.S. President Jimnmy Carter ordered an independent commission to also investigate the accident and they published a voluminous report in October 1979; commonly known as the Kemeny Report.[9] The NRC continued on to not only investigate the TMI-2 accident, but also itself with an internal assessment of its Inspection and Enforcement (IE) office. The NRC published its internal review in December 1979.[10] Here were four reports completed and issued in less than nine months after the accident and there were still more to follow. The new year saw the release of another independently performed investigation although it was contracted by the NRC. The findings were published in January 1980 and referred to as the Rogovin Report.[11] The nuclear industry, under direction of EPRI, investigated the accident and published their report in March 1980.[12] Interestingly, an independent group of engineers examined the findings of the Presidential Kemeny report and also provided their assessment in March 1980.[13] Finally, the NRC utilized all of the preceding investigations to develop an action plan to improve plant operations and regulation.[14]

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[7] U.S. Nuclear Regulatory Commission 1979d.
[8] U.S. Nuclear Regulatory Commission 1979a.
[9] Kemeny 1979a.
[10] U.S. Nuclear Regulatory Commission 1979b.
[11] Rogovin and Frampton Jr 1980a.
[12] Electric Power Research Institute 1980.
[13] American Society of Mechanical Engineers (ASME) 1980.
[14] U.S. Nuclear Regulatory Commission 1980.

In the following sections I examine each of the TMI-2 accident investigation reports. I assess how they engaged with the topic of power plant maintenance programs as they pertained to the safe and reliable operation of nuclear power plants. Given the roles that a clogged water softener, a stuck valve, and a fix action (corrective maintenance) played in the accident, I wished to learn what the NRC and the nuclear industry thought of them. Was their maintenance thinking as informal as the words I just used to describe them? Or had the accident, as an extreme event, reshaped their concept of maintenance to where it was considered critical to safe operations; a critical nuclear system component?

Three Mile Island Unit 2 Accident - NRC Lessons Learned (NUREG-0578 & 0585) - July 1979

Less than four months after the Three Mile Island Unit-2 core meltdown, the NRC's office of Nuclear Reactor Regulation (NRR) published a lessons learned report developed by a task force composed of twenty-two persons representing technical and regulatory branches and divisions from across the NRC. The task force's objective was to quickly assess the TMI-2 accident and identify corrective actions that the NRC and nuclear power plant licenses could implement, across the reactor fleet, in the short-term to "provide immediate, substantial additional protection for the public health and safety."[15] Most significantly, while the report identified several corrective actions, the

[15] U.S. Nuclear Regulatory Commission 1979d, iii.

need for nuclear power plant maintenance as an integrated whole was not identified as a critical lesson learned from the TMI-2 system failure.

The task force identified twenty-three items, requiring action in the short-term, related to seven power plant technical areas:

1. Reactor operations, including operator training and licensing;
2. Licensee technical qualifications;
3. Reactor transient and accident analysis;
4. Licensing requirements for safety and process equipment, instrumentation, and controls;
5. Onsite emergency preparations and procedures;
6. NRR accident response role, capability and management; and
7. Feedback, evaluation, and utilization of reactor operating experience.[16]

The task force stated that “equipment malfunctions, design deficiencies, and human errors…contributed in varying degrees to the ultimate consequences of the accident.”[17] They focused on loss-of-coolant-accidents (LOCA), operational procedures, systems training, and emergency response, since it was a loss of feed water transient, and the operators’ response to that anomaly that contributed to TMI-2’s core meltdown. Items included instrumentation updates to ensure operators understood the condition of the plant systems, automatic initiation of emergency feedwater systems, testing and instrumentation of relief and safety valves, and wide review of operational procedures and operator training. The timeline for implementation of the twenty-three items ranged from just two months for analysis of small-break LOCAs and development of associated emergency procedure guidelines, to most all other items requiring action by January 1980 with some secondary follow-on actions due completion by January 1981.[18]

[16] U.S. Nuclear Regulatory Commission 1979d, 1.
[17] U.S. Nuclear Regulatory Commission 1979d, 1.
[18] U.S. Nuclear Regulatory Commission 1979d.

With these interrelated items under scrutiny, the task force gave indications of recognizing the need for systems thinking and the complexities and interactions of plant components and the operators and engineers running and maintaining them. For example, the effect of maintenance on the safety functions of plant components was noted as was the need for coordination between operators and maintenance personnel to ensure situational awareness of plant operating conditions during maintenance activities. The report specifically mentioned that "operational problems with the condensate purification system led to a loss of feedwater and initiated the sequence of events that eventually resulted in damage to the core."[19] Those operational problems involved maintenance activities on nonsafety systems in the non-nuclear BOP areas of the system. In general, the report described such problems as: "Human error, in the form of improper maintenance, calibration, or test of a safety system, can result in the loss of safety system operability."[20] Specifically, the report put the loss of critical feedwater squarely in the realm of a BOP maintenance error:

> The loss of safety function (emergency feedwater) at TMI-2, caused by two closed feedwater admission valves, is an example of a type of violation of limiting condition for operation caused by human error. In this case, it was not a matter of the loss of a single train or channel in a redundant system, but rather a total loss of an essential safety function.[21]

[19] U.S. Nuclear Regulatory Commission 1979d, 18.
[20] U.S. Nuclear Regulatory Commission 1979d, A-60.
[21] U.S. Nuclear Regulatory Commission 1979d, 21.

The task-force went on to assess that the ”present classification system [designating safety or nonsafety] does not adequately recognize…effects that nonsafety systems can have on the safety of the plant.”[22] Balance of Plant maintenance itself could unexpectedly have the potential to cause or contribute to catastrophic nuclear system failure.

Even when recognizing the complexity and coupling of nuclear power plant systems and components to include balance-of-plant, maintenance was not called out by the task force as a technical area and none of the twenty-three action items specifically addressed maintenance. In a few instances, development and implementation of preventive maintenance programs was recommended, but lack of a preventative maintenance program was never identified as a systemic issue to be addressed by the NRC or plant operators. The NRC's initial look at a nuclear plant accident had brought into view what was thought by the investigators as the immediately obvious human actions and inactions, and component failures that were involved with the accident. The task force had randomly encountered and documented individual maintenance deficiencies, but they did not gather and synthesize these deficiencies into a symptomatic construct that illuminated the need for a formal, technical and programmatic maintenance program that should be a component of every nuclear power plant. Trend analysis may have been done on failures of components and operator performance errors, but assessment of the fundamental structure of the maintenance system was not evident.

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[22] U.S. Nuclear Regulatory Commission 1979d, 18.

In October 1979 the NRC's NRR published the final report of their TMI-2 lessons learned (NUREG-0585).[23] While NUREG-0578 had dealt with safety related actions to be engaged with in the short-term, the final report focused on what the NRR described as "safety questions of a more fundamental policy nature regarding nuclear plant operations and design and the regulatory process."[24] That fundamental policy was one of ensuring "operational safety" through a studied focus on "human factors engineering, qualifications and training of operations personnel; integration of the human element in the design, operation, and regulation of system safety; and quality assurance of operations."[25] The primary lesson the task force described was that the people component of the reactor control system had failed. It was the reactor operators at the control room instrument panels who had contributed to the reactor core ultimately melting. Control design and operator training were two areas identified by the task force for critical improvements. The design of the power plant's interfaces between its hardware components and its human components were deficient. The people components, of the plant, and their supporting infrastructure, were the focus. During the accident sequence, the instrumentation indicated, to the operators, conflicting or ambiguous status of system conditions, thus not allowing them to understand what was occurring as the system failed; not "knowing" the system caused the operators to either not take action or to take inappropriate action that further exacerbated the situation.

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[23] U.S. Nuclear Regulatory Commission 1979c.
[24] U.S. Nuclear Regulatory Commission 1979c, 1-1.
[25] U.S. Nuclear Regulatory Commission 1979c, 1-2.

The task force demanded that the power plant licensees put their full attention on operational reliability and safety. Not only must the operators *know* their systems the management of nuclear power plants must *know* that their operators are fully capable of running a reactor and all of its systems and be able to respond to any condition. The task force's report told its readers that, "Operations is a "hands-on concept."[26] Knowledge and understanding are required of all the people in a nuclear enterprise from the system designers, to the operators at the controls panels, and the maintenance personnel. The report gave little attention to maintenance activities, in fact, the word was only used eight times in the fifty-five page report while "operator" appeared 115 times. The report's most direct recommendation concerning maintenance was in reference to licensee training programs where, "Each licensee should be required to review, within one year, its training program for all operations personnel, *including maintenance* and technical personnel"[27] [emphasis added]. This reference to maintenance seems to be an afterthought. Even with the failure of the condensate system and associated maintenance actions, playing a critical role in the accident, the task force did not identify the effectiveness of maintenance as a fundamental requirement for operating (maintaining) a power plant.

[26] U.S. Nuclear Regulatory Commission 1979c, 1-2.
[27] U.S. Nuclear Regulatory Commission 1979c, A-4.

Investigation into the March 28, 1979 Three Mile Island accident by Office of Inspection and Enforcement (NUREG-0600) - August 1979

The NRC's Office of Investigation and Enforcement (IE) also examined the TMI-2 accident to include a review of the plant's maintenance activities. Headed by the IE director, Victor Stello, the investigation's scope concentrated on two action areas: the actions the TMI licensee took just before the initiating event occurred to when primary coolant flow to the reactor was restored by the operators, and how the licensee controlled radioactive release and implemented its emergency response plan.[28] Stello described the IE report as contributing to overall analysis of the accident by providing additional information to what was given by the NRR Lessons Learned report (NUREG-0578) and also to the future publications of The President's Commission on the Accident at Three Mile Island (the Kemeny Report) and the NRC's Rogovin Report (NUREGCR-1250).[29] The over 800 page IE investigation report concentrated on the accident sequence of events and what actions operators and plant managers took as the accident progressed. The report was quite in-depth and documented not only the actions taken, but the operating conditions of the plant systems, e.g. temperatures, pressures, flows, power levels, and radiation readings. The investigators also examined technical-management areas including system and component surveillance methods, and training activities that were implemented by the plant licensee. Furthermore, with component malfunctions being part of the accident initiating events, the IE investigators

[28] U.S. Nuclear Regulatory Commission 1979a.
[29] U.S. Nuclear Regulatory Commission 1979a.

stated that, "Because the accident of March 28, 1979, involved the failure or malfunction of one or more components, the investigation team performed a review of plant maintenance practices."[30]

The IE investigators examined corrective maintenance practices, but it was not a look at the performance of actual maintenance, as carried out by plant personnel, but was an administrative evaluation. They looked at the general flow of maintenance documentation from its beginnings as "job tickets," through recording of the tickets in maintenance logs, the tickets' assignment to maintenance groups, the tagging-out of service components and systems, the accomplishment of work, and returning the components and systems to service. The evaluation was an audit of the station's administrative and corrective action maintenance procedures documentation, i.e. a scrutiny of how well the maintenance organization annotated its paperwork. That was the metric the IE investigators checked to determine the maintenance effectiveness of the TMI plant. The IE team's report noted a handful of discrepancies in selected components to include: 1) wiring maintenance on the electromatic pressurizer relief valve (the value that failed during the accident sequence) "documentation was not available about how and when the retest was done and the results,"[31] 2) the licensee performed maintenance on the pressurizer heater panels, but "the repair description was not specific,"[32] 3) maintenance on the emergency feedwater valves where, "The investigator did not find suitable documentation as to whether valve cycle, Megger

[30] U.S. Nuclear Regulatory Commission 1979a, I-1-47.
[31] U.S. Nuclear Regulatory Commission 1979a, I-1-50.
[32] U.S. Nuclear Regulatory Commission 1979a, I-1-53.

checks (insulation resistance checks), tagging clearance, and acceptance tests to return the valves to service were performed for the listed valves."[33] This was the extent of IE's examination of the TMI maintenance activities prior to the accident. It was a look at the mechanics of the administration of maintenance processes and not whether or not corrective maintenance was actually accomplished correctly. Beyond the assessment of maintenance documentation, the investigators did identify two program level discrepancies that they classified as "potential items of noncompliance" that did not meet regulatory requirements.[34] One involved having two supervisors of maintenance instead of a single supervisor responsible for both reactor units. The other discrepancy was where Repair Party Teams did not receive training and even when they were trained training was done by an untrained supervisor. The IE investigators did not provide an overall summary of their conclusions on the effectiveness of maintenance or its training even when it seems obvious that both were seemingly ad hoc and unmanaged.

Three Mile Island - Kemeny Report - 30 October 1979

On 05 April 1979, U.S. President Jimmy Carter, a Naval nuclear engineer by training, told the public that he would establish a President's commission to investigate the Three Mile Island accident.[35] The commission was charged to provide: a technical assessment of the accident, determination of role the that the plant's owning utility,

[33] U.S. Nuclear Regulatory Commission 1979a, I-1-55.
[34] U.S. Nuclear Regulatory Commission 1979a, II-F-1.
[35] Walker 2004.

Metropolitan Edison, played in the event, how emergency response actions were executed by the NRC, state and local governments and an assessment of the NRC's licensing and oversight effectiveness at TMI and how the public was kept informed as the accident unfolded. President Carter appointed the president of Dartmouth College, John Kemeny, as the chairman of the committee. The multiple volume report was formally titled *Report of the President's Commission On The Accident at Three Mile Island*, but is commonly known as the Kemeny Report.[36] The report was released at the end of October 1979 and in the areas of investigation it gave insight of how maintenance was managed and conducted at TMI and even how the NRC's processes handled maintenance and how systems were viewed.

Included in the report was the revelation of the absence of a formal maintenance program at TMI and in some shocking instances the absence of any maintenance at all. Like the NRC Lessons Learned report the Kemeny report did not have maintenance as a specific area of investigation; it generally only identified individual maintenance deficiencies. For example, the Metropolitan Edison (Met Ed) maintenance effectiveness was seriously hampered by understaffing. This lack of maintenance resources contributed to the fact that post maintenance quality assurance inspections were not performed on nonsafety categorized systems even when those systems were complex and critical to operations. This was rather understated, even for a safety related components, when the investigators reported maintenance activities where, "the many problems of miswiring, etc., and lack of quality control personnel to provide required

[36] Kemeny 1979a.

surveillance on a safety-related modification is another indication of a less than satisfactory quality assurance program."[37] If sub-standard maintenance was not an obvious indicator of systemic problems then what members of the Commission saw, while touring the TMI-1 reactor in June 1979, was without question evidence that TMI's plant maintenance was in some respects abysmal. The Commission observed leaky "core flood isolation valves in the TMI-1 reactor building [that] had several inches of rusty water standing in the bonnets and boron stalactites/stalagmites, several feet in length, hanging form the valves and building up from the floor."[38] So, it was not at all surprising that the investigators also noted the absence of any trend analysis performed on corrective maintenance actions that could have identified potential problems and possibly predicted failures such as that with the condensate polishing system.

> The lack of a system to report, analyze, correct, and bring to management's attention the failures to equipment and procedural errors not considered safety-related was a significant factor in the March 28, 1979, accident.
>
> The staff review of equipment history…and the staff report on the condensate polisher…clearly show that data was available to management that indicated this equipment was not reliable and had the potential for shutting down the plant and exercising the emergency systems with great frequency.[39]

Even with considerable time spent on examining the role of the condensate system, and its maintenance, as a contributor to the accident, the Kemeny commission did not recommend the establishment of a formal maintenance program as part of its findings. This was remarkable in view of not only the myriad of severely deficient maintenance

[37] Kemeny 1979b, 91.
[38] Kemeny 1979d, 71.
[39] Kemeny 1979b, 83-84.

practices, but also with the Commission's knowledge that a management assessment had been performed on the power plant two years prior to the accident. The GPU Service Corporation (GPUSC), a technical service subsidiary of the electric utility General Public Utilities Corporation (GPU), contracted with the Booz, Allen and Hamilton company to complete a management audit of the plant. Three of its seven recommendations addressed maintenance to include recommending a formal maintenance program:

- The effectiveness of present systems [maintenance] is reduced by their somewhat limited application and use.
- An approach and formal program should be developed to improve the overall effectiveness of the maintenance systems at Met Ed.
- Formal guidelines and minimum standards should be developed to help ensure continued safe, reliable nuclear power plant operations.[40]

The closest the Kemeny investigators approached to providing proposals concerning maintenance improvement were two comments embedded within the report's recommendations, and not as standalone action items:

> Particular attention should be given to such matters as…plant surveillance and maintenance practices; and requirements for the analysis and reporting of unusual events.[41]

> Maintenance inadequacies noted at TMI should be reviewed from the point of view of mitigating the consequences of accidents.[42]

The report's stand-alone observations, engaging with maintenance, were not aggregated and synthesized into the concept of an integrated plant maintenance

[40] Kemeny 1979d, 17-18.
[41] Kemeny 1979c, 64.
[42] Kemeny 1979c, 72.

program. We will see, however, that the observations were carried forward to shape how the maintenance rule was eventually constructed a decade later. The accident at Three Mile Island had begun to gather information to make the critical role of maintenance legible, but the information had not yet coalesced into a recognizable concept in the thinking and actions of the nuclear community.

NRC Report of SRG OIE Lessons Learned from Three Mile Island (NUREG-0616) - December 1979

In June of 1979 Victor Stello announced that his Office of Inspection and Enforcement (IE) would form a Special Review Group (SRG) to assess the IE itself as informed by lessons learned from the TMI accident. He wanted to know what "changes…should be made in IE and in the way IE does business."[43] The focus would include assessment of potential changes to the IE mission, how it thought about and approached inspections, its polices, and the IE organizational structure. In December 1979, the SRG published its internal assessment as NUREG-0616, *Report of Special Review Group, Office of Inspection and Enforcement on Lessons Learned from Three Mile Island*.[44] In the report, there are signs that the IE SRG was constructing their philosophy of maintenance, although decidedly tentatively is some respects, into something that would eventually coalesce and be shaped by the NRC and industry into the maintenance rule a decade later.

[43] U.S. Nuclear Regulatory Commission 1979b, A-1.
[44] U.S. Nuclear Regulatory Commission 1979b.

In the first paragraph of the report's maintenance section the SRG framed the concept of plant maintenance quite straightforwardly by describing its primary intent and how it should work:

> Maintenance of safety related items is an essential function to prevent degradation of equipment and verify continuing operability. Where degradation is detected, corrective maintenance must be performed to restore the safety-systems to a condition which assures availability and adequate reliability.[45]

If a nuclear power plant's systems and components, that are known to be critical to safety, are functioning and running as designed there is a level of confidence that the plant is operating safely and reliably. It is the ability to *know* the condition of systems and components and how they function together either normally or off-normally, that are fundamental challenges for assigning and prioritizing maintenance resources. For example, the SRG investigators noted that the pressurizer's PORV, also called the "Electromatic Relief Valve (EMOV)" was not categorized as a safety related component and yet it was the valve's failure to close that significantly contributed to the accident and its severity.[46] It was the open valve that literally allowed primary reactor coolant to be lost and created the Loss-Of-Coolant-Accident (LOCA). The plant's engineers did not make the PORV/EMOV a priority for maintenance because they had not classified it as a safety related device. The valve had failed because the knowledge and understanding of the plant systems had failed the engineers. System knowledge had also failed the operators because the safety significance of the PORV/EMOV was not legible.

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[45] U.S. Nuclear Regulatory Commission 1979b, 53.
[46] U.S. Nuclear Regulatory Commission 1979b, 2.

It was apparently becoming evident to the SRG that this legibility of plant knowledge and component condition was not something where the nuclear power utilities had predictive technical ability. First failure was often first knowledge:

> The use of Preventive Maintenance (PM) program varies from utility to utility. Some licensee maintenance programs can be characterized as "wait until it breaks, then fix it."[47]

Nuclear plant operators sometimes euphemistically call this "run to maintenance," but "run to failure" is what they actually mean, as I personally heard in a public meeting between the Nuclear Energy Institute and the NRC.[48] If the system is actually run to maintenance, or better yet, run to *preventive* maintenance, it is "fixed" prior to its failure; the system is prevented from failing. Considering this run-till-it-breaks philosophy of the utilities and the SRG's recognition of it, the tentativeness of the SRG's recommendation of preventive maintenance programs is somewhat remarkable.

> The SRG feels that requiring implementation of a preventive maintenance program at licensed facilities should be studied to determine if such a requirement should be universally imposed.[49]

Looking a decade ahead at discussions between the NRC and the licensees, this need to study preventive maintenance, rather than simply mandating it, could be a consequence of government hesitation to make all-encompassing prescriptive regulations over private enterprise rather than performance based regulations, i.e., "We don't care how you prevent plant failures, just as long as you do it." Maintenance must

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[47] U.S. Nuclear Regulatory Commission 1979b, 54.
[48] NEI 2018.
[49] U.S. Nuclear Regulatory Commission 1979b, 57.

be performed effectively by the licensee, where effectiveness means that systems and components function as required to ensure the safe operation of the power plant. Again, the SRG provided another tentative recommendation:

> A survey of all operating plants should be conducted to determine the effectiveness of maintenance programs.[50]

While it did not propose a delaying "study for action," the recommendation for the survey did use the word "should" rather than "must." Here is an indicator of why there was a ten year journey to the implementation of effective maintenance technologies in the nuclear industry. It was directly influenced by the tentativeness of the government's actions.

Three Mile Island - Rogovin Report - 1980

The NRC had its own investigation performed on the TMI-2 accident. In June of 1979, the NRC contracted with the Washington, D.C. law firm, Rogovin, Stern & Huge to independently direct and oversee a critical look into the accident.[51] This enlisting of an external, non-nuclear group a least partially addressed conflict of interest problems with the NRC investigating an accident of a nuclear plant that it directly regulated. While Rogovin, Stern and Huge were not involved in the nuclear industry they did recruit volunteer NRC staff to perform much of the inquiry. The staff's background was reviewed to ensure they were not previously involved with TMI-2 inspections or original licensing activities. The Kemeny report was commissioned by President Carter to

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[50] U.S. Nuclear Regulatory Commission 1979b, 56.
[51] Walker 2004.

provide an external view and assessment of the accident. The Rogovin report was commissioned by the NRC, but with an attempt to provide non-insider objectivity. In addition to the vetted NRC staff, Rogovin also employed outside consultants to provide additional expertise and cross-check findings and recommendations.

Under the oversight of the Rogovin law firm, these nuclear system experts put together a multi-volume document that provided a narrative of the accident. This was the sequence of events from the initial turbine and reactor trips, though the confusion of trying to determine what was actually happening in the plant, loss of coolant through faulty and miss-positioned valves, the often tentative and disorganized Federal response and the realization that fuel had failed and fears of a hydrogen explosion. Examining that unstructured (as became evident as the accident progressed) technical and human activity the investigators also described how the government interacted and informed the public from evacuation plans to a symbolic visit to the site by President Carter. It finally concluded with TMI-2's partially melted reactor core being cooled by natural circulation on 27 April 1979. [52] The Rogovin special inquiry group's critique of this thirty-day drama focused not on failures of TMI-2's equipment and systems, but scrutinized the failure of the American nuclear power plant program. The inquiry became an examination of how the nuclear plant licensees and the government constructed, implemented and ultimately regulated power plant design, operations, and accident response, to ensure safe commercial nuclear reactors. Looking at the Rogovin investigators' recommendations of changes, it was evident that they determined that the

[52] Kemeny 1979a; Rogovin and Frampton Jr 1980a; Walker 2004.

overall nuclear program itself had failed and caused the TMI-2 accident, and not simply a valve, pump, poorly designed control panel, or inadequately trained operator.

The Rogovin SIG concluded that the "changes needed to cope with these problems and attitudes are institutional, organizational, and managerial."[53] They described needed changes that would address gaps in operator training and qualifications, distribution of operating experience knowledge throughout the industry to include experience from outside the United States, emergency response plans and actions, application of quantitative risk assessments in addition to the traditional deterministic design basis accidents methods, and a significant change in how the NRC regulated that would reconfigure their mindset from being primarily a paperwork auditor to an emphasis as being an eyes-on inspector with true understanding of the workings of a nuclear power plant.[54] The Rogovin investigators summarized:

> The one theme that runs through the conclusions we have reached is that the principal deficiencies in commercial reactor safety today are not hardware problems, they are management problems.
>
> [T]he most serious problems will be solved only by fundamental changes in the industry and the NRC.[55]

Here the Rogovin investigators quite plainly did not hide their view that the operational and regulatory aspects of the nuclear program had failed and, indeed, were fatally flawed in the case of TMI-2. What was not as obvious, or as forcefully examined and presented, was the condition of plant maintenance.

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[53] Rogovin and Frampton Jr 1980a, 90.
[54] Rogovin and Frampton Jr 1980a.
[55] Rogovin and Frampton Jr 1980a, 89.

Maintenance Actions

Within the TMI-2 accident analysis, that created the report's overall assessment, the Rogovin investigators did conduct a brief perusal of plant maintenance. They focused on a very few maintenance specific items that appeared to be involved with the accident sequence of events. They also took a cursory retrospective look at previous assessments of nuclear power plant maintenance and safety to assist in putting the TMI-2 activities into a rudimentary context.

First, the group looked at how maintenance might have contributed to the malfunction of the main feedwater loop condensate polishers, whose failure was determined to have initiated the sequence of events that caused the accident. When the polisher system failed it stopped feedwater flow from returning to the steam generators and caused the turbine to trip (shutdown) which in turn caused the primary reactor coolant system to overheat causing the reactor to trip and the pressurizer relief valve to open; the valve that malfunctioned and failed to close when required causing the loss of coolant accident (LOCA). The Rogovin investigators discovered that failure of the condensate system could very have been a result of a poor maintenance program for the system. They determined that there were no specific requirements for "preventive or routine maintenance or qualification of the personnel performing maintenance" on the condensate polishers.[56] So, absence of maintenance or improperly performed maintenance, on this secondary system, could very well have

[56] Rogovin and Frampton Jr 1980b, 49.

contributed to component failures which led to a sequence of events, and other component failures, that caused the LOCA and reactor core damage. Now, since power plant systems are designed with redundancies, loss of the primary feedwater system should have automatically activated a redundant system; in this case the emergency feedwater system. In the TMI-2 accident the automatic emergency feedwater system initially failed and required the reactor operators to manually bring the system online eight minutes into the accident sequence.[57] Here again, maintenance was a suspect in the cause of the feedwater failure.

The emergency feedwater system did not function as intended when the primary feedwater system failed. Valves used to block feedwater flow during maintenance were found to be closed which stopped the flow of emergency feedwater. A maintenance action, performed prior to the accident, that involved the closing feedwater block valves was specifically examined by the investigators where they reported, "[W]e were unable to determine when or how the emergency feedwater block valves-which prevented emergency feedwater from being automatically supplied to the steam generators…came to be closed."[58] The investigators were told by maintenance personnel that the valves *were* closed during routine maintenance, as per standard procedures, two days prior to the accident, but the personnel had sworn to the investigators, under oath, they had reopened the valves at the conclusion of the maintenance. Frustratingly to the investigators they learned that the documentation that would have recorded the closing and reopening of the valves "was routinely thrown

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[57] Rogovin and Frampton Jr 1980a.
[58] Rogovin and Frampton Jr 1980a, 158.

away after the maintenance procedure was finished."[59] It was not mentioned whether or not routine disposal of the maintenance checklist was as per official procedure or whether it was an informal (and unauthorized) action performed by maintenance personnel. No matter if the procedure itself or the personnel were flawed the overall effect was an indication of a potentially flawed maintenance system.

Maintenance History

Considering what they knew about specific maintenance failures of the TMI-2 accident the Rogovin investigators looked at the operating history of the reactor unit. TMI-2 received an operating license from the NRC on 08 February 1978 and the reactor first went critical on 28 March 1978, exactly one year to the day before the accident.[60] The Rogovin investigators looked at historical inspection reports from prior to the accident that dealt with maintenance and maintenance procedures that involved the feedwater and pressurizer systems and associated components such was valves, pumps and seals. During that first year of operation the investigators noted that "TMI-2 experienced at least 20 reactors trips, approximately one-third of which originated in the condensate and feedwater system."[61] The following TMI-2 events are excerpted from what the Rogovin investigators documented:

- Reactor trip due to loss of feed water due to personnel error performing maintenance on feedwater pumps.
- Reactor trip due to loss of one main feedwater pump.

[59] Rogovin and Frampton Jr 1980a, 158.
[60] Rogovin and Frampton Jr 1980a.
[61] Rogovin and Frampton Jr 1980b, 109.

- Reactor trip due to control problems with feedwater pump.
- Two reactor trips [the same day] due to feedwater pump pumps.
- Reactor trip due to loss of feedwater. Personnel error resulted in loss of power to condensate polishing valve.
- Reactor trip due to mechanical failure in feedwater pumps.[62]

These events provide a feel for the unit's environment of reliability and maintenance effectiveness for the feedwater system specifically and also are an indication of the overall health and maturity of the nuclear unit's maintenance program. Stepping back from specific incidents, the investigators also examined systems and maintenance at a higher level.

The Rogovin investigators looked at information related to maintenance from the licensing of TMI-2 and also from broader safety research for light water reactors. They pointed out that during initial licensing review of TMI-2, from 1974 to 1978, the NRC Advisory Committee on Reactor Safeguards (ACRS) had several reservations about the plant. The problems were generic and were to "be dealt with appropriately…as solutions are found."[63] The problems did not prevent licensing of the plant since the ACRS stated "if due regard is given to the items…and subject to satisfactory completion of construction and pre-operational testing, there is reasonable assurance that Three Mile Island…Unit 2 can be operated…without undue risk to the health and safety of the public."[64] The NRC's licensing endorsement was hardly confident with its use of words such as "reasonable assurance" and "without undue risk." The Rogovin team further commented that some of these (apparently acceptable) generic issues related to the

[62] Rogovin and Frampton Jr 1980b, 110-111.
[63] Rogovin and Frampton Jr 1980b, 83.
[64] Rogovin and Frampton Jr 1980b, 83.

TMI-2 accident included "maintenance and inspection of plants."[65] Next, looking at safety and maintenance more generically, the Rogovin investigators noted that in April 1972 the NRC reported to Congress on proposals to increase reactor safety in NUREG-0438, *Plan for Research to Improve the Safety of Light Water Nuclear Plants.*[66] One of the recommendations was to not limit research to operator actions and responses, "but also personnel involved in the testing and maintenance of the plant. It was pointed out that analyses have shown components may be left in an unavailable state by test and maintenance personnel through carelessness, improper training, use of improper procedures or failure to follow procedures."[67] Here was recognition that poor execution by maintenance personnel could have as a detrimental effect on system reliability and safety as component failures from lack of maintenance. The examination of the human interactions with, literally, the nuts and bolts of a nuclear power plant were also a small part of the Rogovin accident analysis.

The investigators noted how human factors were perceived by the NRC as part of effective maintenance. They saw that the 1972 study, WASH-1260, *Evaluation of Incidents of Primary Coolant Release from Operating Boiling Reactors*,[68] in addition to making recommendations for control room design and operator training, "contained a recommendation that licensees and applicants for licenses be required to submit plans and schedules for training of technicians and repairmen engaged in the testing and maintenance of safety related systems and components."[69] With this look at historical

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[65] Rogovin and Frampton Jr 1980b, 83.
[66] U.S. Nuclear Regulatory Commission 1978; Rogovin and Frampton Jr 1980c.
[67] Rogovin and Frampton Jr 1980c, 610.
[68] U.S. Atomic Energy Commission 1972.
[69] Rogovin and Frampton Jr 1980c, 607.

reactor maintenance and summarization of previous studies and their recommendations on improving maintenance, the Rogovin investigators concluded that “the integration of human factors principles and disciplines into all facets of the design, construction, operation, maintenance, testing and regulation of nuclear power plants will significantly improve nuclear safety.”[70] Nonetheless, the Rogovin report only faintly stressed that the NRC “*should* develop an interdisciplinary human factors capability” and “*should* require the development and implementation of formal human factors programs by utilities, vendors, and architect-engineer organizations”[71] [emphasis added]. Finally, in their final recommendation, in their final sentence and the final point (number 13), of their report, the Rogovin investigators stated that the “NRC *should* consider the licensing of auxiliary operators and testing and maintenance personnel for specific plants”[72] [emphasis added]. This was an extraordinary outcome from a group tasked to the find root cause(s) of a complex reactor accident. It is all the more extraordinary since the Rogovin investigators pulled in NRC studies that emphasized the critical importance of human factors in safe operations of a nuclear reactor, to include maintenance. Their own assessment, even when synthesized with that of a previous safety examination did not move the Rogovin team to mandate human factors programs for either the industry or the NRC. Maintenance, as a safety critical technology, was not fully registering with the nuclear community.

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[70] Rogovin and Frampton Jr 1980c, 612.
[71] Rogovin and Frampton Jr 1980c, 612.
[72] Rogovin and Frampton Jr 1980c, 613.

Within their multi-volume report the Rogovin investigators tended to examine TMI-2 maintenance as isolated events; it was not in an all-encompassing manner that treated maintenance as a technical and management entity itself. Maintenance activities were, for the most part, examined as individual actions, but maintenance overall was not assessed in its effectiveness as an integrated, programmatic system. They rather disconcertingly noted that, "Another deficiency is the lack of specific criteria for preventive and corrective maintenance programs, surveillance testing, and other operational activities for ensuring the quality of these activities."[73] Clearly, without standards criteria a technical program, maintenance or otherwise, does not practically exist. The investigators went on to comment that inadequate preventive maintenance could be attributed to failures of safety-related components and that the "problem is compounded by the lack of specific qualification requirements and certification of personnel performing these activities."[74]

Even with the observations of fundamental deficiencies in how maintenance was designed and implemented, the Rogovin investigators did not seem to fully support their own assessment that:

> The fact remains that nuclear technology is different in kind from the traditional technology of electric generation by fossil fuel and hydroelectric means-more dangerous, more sophisticated and more demanding of advanced management, maintenance, and quality control.[75]

[73] Rogovin and Frampton Jr 1980b, 45.
[74] Rogovin and Frampton Jr 1980b, 45.
[75] Rogovin and Frampton Jr 1980a, 110.

While stating the criticality of maintenance for nuclear systems they did not pull their assessment together into a whole that recognized the need of a mandatory nuclear power plant maintenance program. They did not construct an unequivocal mandate.

Three Mile Island – Electric Power Research Institute (EPRI)

> Good practices in equipment, maintenance, management and operation are the rule rather than the exception. However, lapses from good practice do occur.[76]

With these two short sentences the TMI-2 accident itself, and any potential relationship of it with maintenance, was characterized as being an inadvertent interruption of a normally good nuclear operating routine. That was the Electric Power Research Institute's (EPRI) Nuclear Safety Analysis Center's (NASC) overall causal assessment of the accident they gave in their March1980 report, *Analysis of the Three Mile Island Unit-2 Accident*.[77] In fact, this was the only time maintenance, as an activity, was mentioned in the 500 page document. The several hundred pages do provide an extremely detailed, event by event, operator action by operator action, and minute by minute, narrative of the accident sequence. Beyond the focus on power plant mechanics and the action of the operators, there are two events in the narrative that could be indirectly related to maintenance and one event that is a direct indicator:

- Failed components (potentially attributable to ineffective maintenance or errors in maintenance performance):

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[76] Electric Power Research Institute 1980, iii.
[77] Electric Power Research Institute 1980.

A condensate pump…tripped off-line—that is, stopped operating.[78]

The decrease in pressure should have caused the relief valve on the pressurizer to close automatically when the system reached normal operating pressure. But for reasons not yet known, it stuck open.[79]

- Maintenance error:

On this occasion, the block valves downstream from the auxiliary feedwater pumps…had inadvertently been left closed after a required test operation which involved closing these valves?[80]

None of these events were described in terms of maintenance by the NASC investigators. It is interesting that the closed feedwater block valves are quite evident as being a maintenance related problem and could definitely be characterized as a lapse of good maintenance practice.

The NASC accident reviewers also summarized their recommendation for improvement in nuclear power plant operations and safety in two sentences:

The basic remedy for the evident deficiency shown by the Three Mile Island accident can be expressed as follows: It is essential that the good practices of the industry - in equipment, management and operation, which are generally observed by most utilities - be rigorously extended to all, and that the frequency of lapses from good practice be reduced. However, perfection is not necessary.[81]

This mirrored their causal analysis and further emphasized that they believed accidents will normally occur. The NASC was stating that the current system of commercial nuclear management, operations, and maintenance, was working well. Any failures, such as TMI-2, was within the tolerances of normal lapses and acceptable imperfect perfection. Maintenance was not even considered a notable actor by the NASC.

[78] Electric Power Research Institute 1980, Exec. Summary - The Accident, third page. Pages are unnumbered..
[79] Electric Power Research Institute 1980, Exec. Summary - The Accident, fifth page. Pages are unnumbered..
[80] Electric Power Research Institute 1980, Exec. Summary - The Accident, fourth page. Pages are unnumbered..
[81] Electric Power Research Institute 1980, iii.

Three Mile Island - Report of Engineers' Committee on Three Mile Island

Immediately after publication of the President's Kemeny Report members of sixteen professional engineering groups in the United States assessed the report under coordination of the National Society of Professional Engineers (NSPE).[82] The report was not the position of the individual societies, but the professional assessments of the engineers themselves. They wished to provide an independent engineering view of the Kemeny assessment and other reviews of the TMI-2 accident (they also looked to assess the Rogovin investigation and the Senate's Subcommittee on Nuclear Regulation). The group focused on areas of: system design, construction, operation and maintenance, system safety management, emergency management, and regulation and legislation.[83] While agreeing with the Kemeny report's assessment that fundamental change was needed with the nuclear industry and its regulation the committee made further recommendations to include: use of a systems engineering approach to plant design, construction, operations and maintenance; emphasis on human factors engineering and; enhancement of emergency management planning and implementation. For this discussion, the committee's complete comment on improvement of maintenance deserves attention with its originally underlined emphasis:

> <u>The "long-term neglect" of maintenance that was reported at TMI-1 deserves more attention than it was originally given</u>. The safety and performance of nuclear systems are dependent upon the adequacy of the maintenance programs utilized for the prevention and the correction of systems failures. The NRC, industry and manufacturers should give more attention to the engineering development, review and

[82] American Society of Mechanical Engineers (ASME) 1980.
[83] American Society of Mechanical Engineers (ASME) 1980.

control of maintenance plans, procedures, training, equipment and management to assure the reliability and safety of nuclear systems. This not only requires close integration of the maintenance engineering and maintenance management functions, but also requires a systems engineering approach which utilizes reliability and systems safety engineering, data and analytical techniques. During the regulatory process, the system design process, and throughout the operating life of the system, constant consideration should be given to the planning, control and implementation of maintenance functions[84] [emphasis in the original].

With this assessment, the committee's engineers, most of whom were not nuclear specialists, showed that they viewed a nuclear power plant not simply as an industrial-mechanical artifact with commercial objectives and break-fix management, but as a socio-technical system with the technology of maintenance as an integral structural system component. In this conceptual realm maintenance is not "something" that laborers "do" on the power plant; it is a constituent system element of the plant that is "operated" by maintenance personnel and interacts with all other system components. Maintenance is not a bolt-on, after-the-fact, back-fitted project. It must be, and is, inherent to an effective system. The engineers' committee understood that maintenance is in the fabric of a system's life from its initial concept through its end-of-life; without maintenance an effective and safe system does not practically exist.

The committee's evaluation is by far the closest that any assessor of the TMI-2 accident came to identify the critical importance of a formal maintenance program to the safe and reliable operation of a nuclear power plant. Closest, but even with their perceptive assessment they did not explicitly state the need for a formal maintenance program. Like others, they softened their "demands" to "recommendations" with

[84] American Society of Mechanical Engineers (ASME) 1980, 4.

wording such as: “should give more attention” and “constant consideration should be given.”[85] Nonetheless, the engineers explicitly recognized the fundamental requirement for fully integrated and comprehensive maintenance programs. With the engineers as the only outlier in the accident assessments how did the NRC react, in its regulatory capacity, to the evaluations as a whole?

NRC TMI Action Plan Vol 1 & 2 (NUREG-0660) - May 1980

In just a few months, the NRC consolidated the recommendations of the previously discussed investigating groups, and others, and published them in May 1980 as the, *NRC Action Plan Developed as a Result of the TMI-2 Accident* in two volumes (NUREG-0660) with the NRC’s staff’s or Commission’s assessment. The action plan had little if anything to add concerning maintenance. Its objective was “to correct or improve the regulation and operation of nuclear facilities based on the experience from the accident at TMI-2,” but it did not take into account information from non-governmental reports such as those from EPRI and the Engineers’ committee on TMI-2.[86] Furthermore, it categorized the reports’ recommendations into areas to include power plant operational safety, siting and design, emergency preparedness, and overall NRC practices, policies and the organizational structure, but it did not explicitly call out maintenance as a significant area requiring action.[87] That might have been expected

[85] American Society of Mechanical Engineers (ASME) 1980, 4.
[86] U.S. Nuclear Regulatory Commission 1980, 1.
[87] U.S. Nuclear Regulatory Commission 1980.

given that the reports themselves did not heavily engage with maintenance, but the action plan's method did provide an opportunity to fill the maintenance gap.

The action plan's staff examined recommendations in each area and made assessments as to if the recommendation was satisfactory or covered under current policies and procedures, or if the staff did not agree with the recommendation, or if it was outside of the scope of the NRCs responsibility. In nearly two-hundred pages of cross-tabulated assessments, the action plan took maintenance references and recommendations at face value. The action plan staff concurred with the few recommendations regarding maintenance and did not fault any recommendations for being less than comprehensive or requiring more urgency in implementation. For example, in assessing the IE SRG's recommendation to study the need for preventive maintenance programs the action plan stated that, "[This] recommendation is adequately covered under actions in the referenced task…."[88] Further, the action stamped the SRG's recommendation to survey power plants for maintenance effectiveness with, "This recommendation will be taken into consideration in ongoing IE work."[89] Here we see two tentative maintenance recommendations endorsed with further tentativeness of action. Nothing more was added to recommended improvements, or for that matter even *plans to consider* improvements, by the action plan. If we conceptually consider the action plan assessments as quality control checks on actions to improve maintenance then we might question their effectiveness; as we may question the effectiveness of nearly all of the investigations if limited

[88] U.S. Nuclear Regulatory Commission 1980, 113.
[89] U.S. Nuclear Regulatory Commission 1980, 113.

uniquely to providing impetus for development of a maintenance program.

How the Reports Evaluated Maintenance

How did the TMI-2 accident studies assess maintenance? For the most part they did not. If maintenance was mentioned it was almost in passing. In the reports, maintenance is treated as a "bolt-on" activity where the word itself was generally buried within a sentence that contained the primary words "operations" and "maintenance." It was also nearly always paired with the preceding word "including." Practically speaking, it was not used singularly as a word or as a topic. With the exception of the Engineer's Committee Review, all of the immediate studies of TMI-2 did not examine and treat maintenance as a fundamental and critical system activity. The idea of a systemic maintenance program was still not a functioning concept (or apparently contemplated) even with maintenance problems identified as contributing to the accident. As we will see, it would take over a decade for maintenance program thinking to be established by the NRC and industry in the commercial nuclear power environment. Therefore, looking back at this, it is not entirely surprising that the TMI-2 investigations did not suddenly construct the idea, or realization, that a maintenance program was critical to safe nuclear power plant operations. It appears that the beginnings of maintenance program thinking started much more mundanely than with a reactor core meltdown. It began with an organizational policy plan and the TMI-2 investigations initially playing a supporting role. Those in the NRC who were looking at maintenance were not oblivious to the TMI-2 reports and what they did say about maintenance.

NRC Subcommittee on Maintenance Practices and Procedures - 08 May 1984

> MR. REED: I shudder to think that there are nuclear plants out there that do not have the rudiments of preventive maintenance program all established before they go critical.[90]
>
> - G. Reed, member of the NRC Subcommittee on Maintenance Practices and Procedures

In January 1984 the NRC published the third annual issue of its Policy and Planning Guidance (NUREG-0885, Issue 3).[91] The purpose of the guidance was to provide all those in the NRC with knowledge of the organization's primary goals and objectives for the year; it framed the activities for each office of the NRC. With its primary task of ensuring that nuclear facilities did not adversely affect the public's health and safety, the NRC put the Subcommittee on Maintenance Practices and Procedures, under the NRC Advisory Committee on Reactor Safeguards, to oversee the development of a draft Maintenance Program Plan (MPP) for nuclear power plants. The subcommittee was directed by the Policy and Planning Guidance's objectives of assuring safe operation of plants and improving their quality through: 1) a "focus on the operations of licenses, including maintenance activities," 2) a "review a human factors program plan element which proposes alternative NRC regulatory approaches with respect to maintenance activities"[92] and, 3) "inspection activities [that] focus more attention on maintenance and

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[90] U.S. Nuclear Regulatory Commission 1984a, 45.
[91] U.S. Nuclear Regulatory Commission 1984c.
[92] U.S. Nuclear Regulatory Commission 1984c, 4.

surveillance activities in plant operations, including preventive maintenance."[93] With the NRC's mission intent laid out, the subcommittee moved forward with developing a draft Maintenance Program Plan. By late Spring 1984 a draft plan had been developed and was ready for review.

On 08 May 1984, in Washington, D.C., the subcommittee and power plant subject-matter-experts held a daylong meeting to discuss and deliberate a draft of the plan; the Maintenance Program Plan (MPP).[94] These discussions, made available through a three-hundred page transcript, give an insightful and candid record of how maintenance was understood by the NRC and how they began to conceptually construct a nuclear power plant maintenance program; a program that did not exist in the American commercial nuclear environment. They candidly described the regulatory problem as one where "maintenance concentrates on…quality assurance (QA) during design, construction, and operation for structures, systems and components important to safety (10 CFR, Appendix B) and…surveillance requirements to assure…the…availability and quality of…systems and components."[95] What they found fundamentally wrong with this regulatory structure was that the "NRC rules and regulations provide no clear programmatic treatment of preventive maintenance."[96] Furthermore, there were no NRC maintenance requirements for non-safety related systems and components, such as those in the Balance-of-Plant (BOP), and this was precisely the area where the TMI-2 accident was initiated. In the MPP the subcommittee made it clear that the TMI-2

[93] U.S. Nuclear Regulatory Commission 1984c, 5.
[94] U.S. Nuclear Regulatory Commission 1984b.
[95] U.S. Nuclear Regulatory Commission 1984b, 2.
[96] U.S. Nuclear Regulatory Commission 1984b, 2.

accident was (what I would describe as) the *recognition event* that maintenance was critical for safe plant operations, "Ever since the Three Mile Island accident in 1979, it has been evident that faulty maintenance practice is a principal contributing factor to operating abnormalities."[97] Although, it appears, at this point, that the subcommittee has a somewhat narrow view of maintenance where it focuses on a specific deficient practice rather than a maintenance program. Also, from the Rogovin report, the sub-committee re-publicized that maintenance was the initiating event of the accident by capturing the quote:

"The initiating event for the Three Mile Island (TMI) accident involved maintenance on the condensate polisher system (Rogovin and Frampton, 1979)."[98]

In the MPP, the NRC had reached back to a TMI-2 investigation (the Rogovin Report) for a key piece of evidence that coupled the accident to maintenance. They used this link as empirical support for development of the MPP. Maintenance was shown to be both a precursor to the accident, well upstream of 28 March 1979, and an immediate contributing cause to the accident. It was a precursor due to the lack of an effective maintenance program that set the conditions for ineffective corrective maintenance, and hence the accident. It was also a direct initiator caused by ineffective (incorrectly accomplished) maintenance itself. Rather than being started by a direct mandate from TMI-2 investigations for a maintenance program, the NRC's normal organizational mechanics had initiated program development. The investigations provided foundational assessments that placed effective maintenance programs as being

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[97] U.S. Nuclear Regulatory Commission 1984b, 3.
[98] U.S. Nuclear Regulatory Commission 1984b, 4.

fundamentally consequential and therefore at the core of safe plant functioning. With this regulatory problem set in mind, the subcommittee engaged with a definition of maintenance and six technical issues to be addressed in the development of the final Maintenance Program Plan.

Significantly, it was the absence of an explicit definition of maintenance that had allowed the commercial nuclear industry to not prioritize maintenance and severely limit NRC regulatory oversight. The MPP was the NRC's first attempt to formally define maintenance in detail:

> Maintenance:
> Maintenance is defined herein as a function with the objective of preserving the inherent reliability and safety of plant structures systems and components or restoring that reliability when it is degraded. Maintenance includes: (a) diagnostic or periodic testing, surveillance and inspection to determine the condition of structures, systems and components, (b) preventive or corrective actions such as repair, replacement, lubrication, adjustments, or overhaul, and (c) proper equipment isolation, restoration to service, and post maintenance testing to assure adequacy of corrective action. Maintenance is performed during all modes of plant operation by plant staff, vendors, or contractors.[99]

Within the framing of this maintenance definition the NRC subcommittee group reviewed and discussed six areas of technical issues: 1) Human error, 2) indicators of maintenance effectiveness, 3) aging and preventive maintenance, 4) how management and organization affects maintenance effectiveness, 5) maintenance program standards and, 6) verification of correctly performed maintenance and how maintenance interfaces with operations.[100]

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[99] U.S. Nuclear Regulatory Commission 1984b, 7.
[100] U.S. Nuclear Regulatory Commission 1984b.

Maintenance Concerns

The issues prompted not only technical discussion about the specific topic, but had the participants thinking aloud generally. This provided a glimpse into their professional experience, primary interests, what they were contemplating and, candidly, what they did not know or understand. The NRC group was grappling with the conceptual framework that would build a maintenance program. The following are excerpts from the subcommittee's transcribed discussion about each issue and my thoughts about each:

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Issue 1

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Human Error in the Performance of Maintenance…(97/14)

> MR. BOOHER: We have defined that as events caused by inadequate, incorrect, or lack of maintenance personnel activity.
>
> MR. KERR: To what level do you plant to reduce it?
>
> MR. BOOHER: We have not established that level yet. First of all, we have not even gotten real good ways of measuring that consistently.
>
> MR. KERR: What we know in a general case is that human error contributes to unreliability. I do not have any idea of whether there is an unusual amount of human error in the maintenance of nuclear power plants, or the usual amount. And if we try to reduce it below what one is — what humans are capable of, we may be in a losing game. This is the reason

that I asked to what level do we expect to reduce it. It seems to me that we need to know, before we try to reduce it, how low it is possible or feasible to reduce it. [101]

A certain error level was considered unavoidable and a normal aspect of doing business in a power plant. As Kerr put it, there was a "usual amount," but just what it should be and how they would know was yet to be determined. What was the tolerable level of error that still provided for effective maintenance? Were they assuming (hoping?) that the always present background errors would be discovered, prior to failure, by testing, surveillance, quality assurance inspections and preventive maintenance? To enable these methods of error detection a formal system of maintenance standards, training to those standards, and, what is often not considered, standards of training would be required to be implemented by the industry, in other words a maintenance program.

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[Question to Mr. Booher]
MR. MICHELSON: Are they making more mistakes for a similar situation in a nuclear plant than they would have in a fossil plant or in an automobile factory or wherever? Are we seeing more mistakes, about the same or less? Or do we know?

MR. BOOHER: I don't know. Do we have anyone who knows?

MR. MICHELSON: If I am seeing it considerably higher than elsewhere, then there is something funny going on in a nuclear plant that ought to be corrected.

MR. BOOHER: That is a good question. From what I can glean from the people talking at the INPO workshop, I suspect there would be higher errors because of lower motivation in

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[101] U.S. Nuclear Regulatory Commission 1984a, 97-100.

> nuclear plants, when they had a choice between working one or the other the access problems they had and the overall problems that they had with paper, filling out — I would expect a higher error rate.[102]

Michelson's and Booher's discussion point out that the nuclear industry, to include the regulator, had not considered to formally benchmark their maintenance performance. But, there is an anecdotal benchmark, and it is striking; Booher's comment about lower worker motivation in a nuclear plant. He has informally used the human factors of maintenance in conventional plants as a benchmark for comparison to nuclear. He was referring to his earlier observations to the committee where he stated:

> There has been good maintainability designs put in early in the plants. And then, because of the resource limitations, the access ladders and these things are removed at the last minute from the design because of cost savings.
>
> If you have fossil plant as well as a nuclear plant, who wants to go work nuclear when you can get the same pay and you do not have all of these problems.[103]

Here are indications that cost saving constraints makes for a physically and administratively more difficult to maintain power plant. Physically, in this case, due to lack of maintenance access ladders and administratively because it is costly and time consuming to develop, implement and maintain a maintenance program; a program that could optimize procedures and minimize the amount of paperwork required to document and perform tasks.

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[102] U.S. Nuclear Regulatory Commission 1984a, 105-106.
[103] U.S. Nuclear Regulatory Commission 1984a, 59-60.

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Issue 2

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Indicators of Maintenance Effectiveness…(14)

MR. BOOHER: A definition of an indicator is a measure of, again, something very difficult to measure. We call it the goodness of the plant maintenance performance. The present indicators are incomplete and direct. Such things, even as the scram rate, IE inspections, SALP [Systematic Assessment of Licensee Performance]…

> MR. EBERSOLE: The scram rate and trip rate is the culmination of a situation which should not have been allowed to get that far.
>
> MR. BOOHER: Right.
>
> MR. EBERSOLE: So you will not pick it up, if they use that as the only indicator.
>
> MR. BOOHER: It is the ultimate indicator.
>
> MR. EBERSOLE: Yes.[104]

Ebersole sees that Booher's "ultimate indicator," reactor scram, is not the best signal for assessing *progress toward* "maintenance goodness" since it is at the end of a chain of system redundancy and safety functions. As he points out, there are numerous maintenance affected components and systems that are links in that chain and that is where a maintenance program must be built.

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Issue 3

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Counteracting Aging Effects and the Role of Preventive Maintenance (15)

[104] U.S. Nuclear Regulatory Commission 1984a, 110-111.

MR. BOOHER: “Again, definition of aging: degradation of equipment performance due to lack of maintenance. And preventive maintenance is activities performed to counteract aging and normal wear.”

MR. EBERSOLE: “I have trouble with that definition of aging, because it is not consistent — other IEEE or equipment qualification work, which is the effect of again, per se. The influence of time and the environment versus wear-out, which is a different thing. Isn’t that — aging is not used in that context, in the broader sense and I think something ought to be said about that.”

MR. BOOHER: “John, you put that definition down. Do we have a special reason for that, so we can show an improvement?”

MR. EBERSOLE: “Aging is insulation getting old and stiff and rubber getting hard due to radiation and other environmental effects, effects of temperature and time et cetera, et cetera.”

MR. JANKOVICH: “Yes, we agree with that definition. Why we put it in this context, at the moment, is that we want to emphasize those aspects of aging which could be counteracted by preventive maintenance.”

MR. EBERSOLE: “By replacement on cyclic intervals?”

MR. JANKOVICH: Yes. I just want to be precise with that case. It cannot be counteracted when it comes to pipe cracking — “

MR. EBERSOLE: “For instance — “

MR. JANKOVICH: “Or corrosion or when it comes to seals or pump maintenance at the original performance level, that could be counteracted.”

MR. EBERSOLE: “This is oriented to periodic replacement before aging occurs?”

MR. JANKOVICH: “Yes.”[105]

The discussion shows that system definitions, while certainly not unknown, were still being precisely worked out in people’s minds. With the Maintenance Program Plan the NRC was beginning to document the construction, in a pre-regulatory plan, the system intercoupling of component conditions, their relationship to system life (aging), and how preventive maintenance is an integral part of that system. Here, a conceptual difference of component aging, in a passive sense from the effects of environmental conditions, is contrasted to to that of components actively wearing in a system as it operates over time. The discussion indicates that wear of components is typically addressed through preventive maintenance while aging, e.g. the cracked pipe, is engaged with corrective maintenance. They go one to say that preventive maintenance could also be used to address the effects aging by replacement of deteriorated parts. I would characterize that as environmental wear.

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Issue 4

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Management and Organization Impacts On Maintenance Effectiveness (17)

> MR. BOOHER: It was decided that the NRC does not have the analysis methods or expertise to correct the management related to maintenance problems. Our reviews are typically after the fact evaluations of problems that rely on utility self-analysis or analysis by

[105] U.S. Nuclear Regulatory Commission 1984a, 111-112.

consultants. The scope here would be getting into things like planning and scheduling, chain of management as they relate to or impact maintenance.

MR. MICHELSON: Is the concept of the designated representative, as used in the FAA, going to apply in some respect here?

MR. BOOHER: I'm not real familiar with what that is.

MR. MICHELSON: I will let Glenn pick up from here. He is the disciple of it.

MR. REED: The gentlemen from the Staff who spoke earlier about certified mechanics in the FAA. And that is sort of a designated representative. It is a motivator. It is important. I believe in designated representatives in all departments, let's say if they do not already have them in the operating plant. And I always think of the operating plant as having licensed operators who are essentially designated representatives anyway. If we just change the wording on their license a little bit, designated representative are important. And in my way of thinking, they are more important than key component manufacturers…and designers of facilities right now.

MR. BOOHER: We certainly would want that. It sounds like a good practice.

MR. REED: Certainly it has a very close coupling with human factors. After all, you cannot. — what is it, the old saying you can lead a horse to water but you cannot make him drink. You can put a person at the equipment to do repair, but if he is not motivated and dedicated and so on, he will not do a good repair.

MR. EBERSOLE: Nuclear power plants are full of pumps and valves. I see it as hopeless to anticipate we will have any certified mechanics to pick up all of that. But the designated representative, we could go through the formalization of the certification requirements to have the nucleus of maintenance formalized with an overview toward those fellows who actually did the details. Was this what you were thinking about, Glenn? With the designated representative? A certified individual?

> MR. REED: I'm not sure that the certificate could not be informal. It could be recognition as the leading person by his peers and by the management of the company and he has no conflict of interest, with respect to applying his trade with diligence and quality.[106]

Similar to the situation with scram as the "ultimate indicator" of maintenance effectiveness, the NRC was engaging with maintenance management too far removed from the problem. It was assessing organizational activities downstream of their origin due to deficiencies in their own organizational knowledge and technique. Here they have identified a potential method to mitigate the problem by moving upstream with "designated representatives" who provide expertise that is "certified" by the regulator, but also locally trusted by the operator. As we will see, in the late 1980s, after the NRC had formally proposed the Maintenance Rule, they also examined the maintenance methods of other technical organizations to include the U.S. military and foreign power plant operators. The NRC published the assessment as NUREG-1333, *Maintenance Approaches and Practices in Selected Foreign Nuclear Power Programs and Other U.S. Industries: Review and Lessons Learned,* in early 1990.[107]

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Issue 5

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Maintenance Program Criteria and Standards (17)

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[106] U.S. Nuclear Regulatory Commission 1984a, 112-116.
[107] U.S. Nuclear Regulatory Commission 1990.

> MR. BOOHER: The fifth issue is maintenance program criteria and standards. This is probably the biggest area that we would have NRC involvement in, how do we establish the minimum threshold for NRC and industry to use for acceptable maintenance performance….The basis, of course, is the current fragmented approach. We need to come up with an integrated approach to maintenance that includes all the elements of the program, and our goal here or intent would be to provide those tools for enforcement, like workbooks or guidelines, inspection modules, good practices, these kinds of things as our criteria and standards. It may be if industry comes up with a standard in this area, we could write a reg guide to go with that. Again, it is a starting point. If we do not have that, we do not have much.[108]

Booher summed up the programmatic nuts-and-bolts requirements for maintenance standards and methods. These would form the fundamental base of the maintenance program's structure of: periodic testing, preventive maintenance, maintenance execution, and post-maintenance return to service. This was also critical in that it was the beginning of a true formalized maintenance framework.

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Issue 6

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Verification of Correct Performance of Maintenance-Related Activities and the Operations Interface (18)

> MR. BOOHER: The final issue was the one of verification of correct performance of maintenance—related activities and the operations interface. We have been over this a number of times, and again, the wrong [not legible] is a problem. We have had a couple of TMI action items, and I understand these do not seem to be totally adequate and we need to

[108] U.S. Nuclear Regulatory Commission 1984a, 117.

look again at Reg Guide 1.47, how it is being used in the industry, and the whole intent is to improve availability of safe systems.[109]

Here we see practical recognition that maintenance personnel are essentially co-operators of a nuclear power plant. Maintenance functions are as much an integral part of a nuclear power plant system as are operations. The awareness of the interface with operations is a fundamental of performing *and* coordinating maintenance safely and to standard. That coupling was dramatically brought to the nuclear community's attention by the TMI-2 accident. Maintenance tags obscured the TMI-2 operators control panel indicators and feedwater block valves were not opened after maintenance. The maintenance team knows that a system is "down" for maintenance or is in a maintenance configuration that affects normal functional operations. This must also be, without fail, communicated to the control room operators so they know not only about the maintenance activity, but how it affects systems operations. Has a redundant system been taken offline? Is a normally automatic function now in manual mode that requires direct operator actions for function? What has changed? The "operational" maintenance actions, and subsequent practical control, must be integrated with standard operations.

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MR. BOOHER: These are the six issues, and I think before we go any further, I would like to see whether or not the Committee feels that these issues in the broadest sense would cover all of the things that you think relate to maintenance….

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[109] U.S. Nuclear Regulatory Commission 1984a, 118.

> MR. KERR: It seems to me these form a reasonable framework from which to proceed. You yourself have pointed out a number of things that have to be worked out.
>
> MR. MICHELSON: There are six of them. There is enough choice that almost anything you dream up would probably fit into one of the six categories that you have.[110]

The MPP laid out a five to six year timeline of its defined activities for both industry and the NRC. For industry it was activities that would be directly affected by the MPP: 1) plant maintenance, 2) aging of plant components, 3) scram rate and safety system cycling, and 4) technological progress.[111] The NRC activities included tasks for the development of the MPP itself, regulatory analysis and the implementation of a regulatory decision concerning nuclear power plant maintenance by mid-1988.

Planning to Rework Maintenance

On that path to a planned decision making ability in 1988 and to work toward meeting the maintenance requirements of the 1984 Policy and Planning Guidance, the NRC developed a Maintenance and Surveillance Program Plan (MSPP).[112] The objective for constructing the MSPP was "to provide direction for the NRC's efforts to assure effective nuclear power plant maintenance and surveillance."[113] The MSPP was to be the guide for a baseline survey of industry maintenance practices. The NRC needed to actively and formally assess what was actually occurring at commercial

[110] U.S. Nuclear Regulatory Commission 1984a, 117-118.
[111] U.S. Nuclear Regulatory Commission 1984a.
[112] U.S. Nuclear Regulatory Commission 1985.
[113] U.S. Nuclear Regulatory Commission 1985, Page 1 of enclosed MSPP.

nuclear plants in regard to maintenance activities. Since the TMI-2 accident the NRC had only been slowly and incrementally looking toward engaging with deficiencies in maintenance. With the strategic 1984 Policy and Planning Guidance, the NRC made maintenance an actionable item at the tactical, staff level, by supporting allocation of resources and initiation of projects, as is the normal the case in any government agency. Significantly, the plan was beginning to redefine how maintenance was viewed and performed by both the NRC government regulator and the private nuclear power industry. William Dircks, the NRC Executive Director for Operations, in his memo to the NRC Commissioners, described this nascent view of maintenance as:

> The plant maintenance activities addressed In the MSPP Includes those plant functions required to carry out a systematic maintenance program. It extends, therefore, beyond the conventional corrective and preventive maintenance and repair to Include functions such as surveillance and testing, operations/maintenance interface, maintenance management. procedures, and technical documentation.[114]

Maintenance was to be conceived, by all involved, as considerably more than simply turning a wrench to tighten a leaking valve. There are many who are participating. It is not just the wrench turner; the maintenance specialist. The wrench manufacturer must ensure the tool is reliably functional, especially if it is a calibrated instrument such as torque wrench. The engineers, who designed the valve, must determine the correct torque value to be set on the wrench so the valve does not leak if

[114] U.S. Nuclear Regulatory Commission 1985, 2.

tightened insufficiently or fracture if over tightened. The technical procedure writer must ensure that the valve maintenance task is understandably written to document the acceptable range of torque values. The plant training manager must ensure a formal maintenance training program is in place and that the maintenance technician has been properly trained on the valve maintenance task using the correctly designed procedure. Maintenance management personnel must be aware of potential difficulties in performing the task, i.e. is the valve in a difficult (often hazardous) location to access and could that increase the likelihood of the maintenance technician making a mistake? Management must also construct trending analysis that can make legible the root cause of the valve failure. Perhaps it was a maintenance caused failure due to insufficient training or environmental conditions? It could have also been engineering failure of the valve itself in which case the valve manufacturer must become involved in resolution. Also, were the control room operators aware of the valve failure and the in-work maintenance task? With the failed valve, did the operators understand the effect(s) on the plant they were operating? Finally, the failure and resolution knowledge must be turned into maintenance operating experience (OE) to be shared across the nuclear enterprise. All must know and understand.

As the NRC was working through the development of the MSPP, the nuclear industry formed the Nuclear Management And Resources Council (NUMARC) as their policy advocate. They immediately began to contribute to the environment of maintenance knowledge and understanding. NUMARC actively engaged with the NRC by providing feedback on draft versions of the MSPP and also by ensuring that the NRC was aware of industry initiatives focused on maintenance activities. Those initiatives included looks at operational events and failure data, performance indicators, procedure writing, training, and sharing of effective maintenance practices.[115] With the MSPP, the NRC specified it was engaging with six technical issues:

- Human error In maintenance
- Indicators of maintenance effectiveness
- Role of preventive maintenance in counteracting aging and service wear effects
- Management and organization impacts on maintenance effectiveness
- Maintenance program criteria and standards
- Maintenance and operations interface[116]

With the collaboration of the industry it was not surprising that these issues aligned closely with what the nuclear plant licensees were also considering. What is surprising is the NRC's rather candid explanation of why they developed this particular list of critical issues:

> [The] six technical issues in nuclear power plant maintenance practices were identified on the basis that they are common occurrences, but have no solution at the present time, received inadequate attention in the past, and may warrant NRC attention in the future.[117]

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115 U.S. Nuclear Regulatory Commission 1985.
116 U.S. Nuclear Regulatory Commission 1985, 2.
117 U.S. Nuclear Regulatory Commission 1985, 2.

Here are known problems at, implicitly, all of the country's nuclear power plants. They are not only not new, but they are not unusual. What is extraordinary about the NRC's description of the problems is that they straightforwardly say there are currently *no solutions to resolve them*. That is typically not how government agencies, especially those charged with regulating aspects of public safety, talk about problems. This indicates that they were ready to more aggressively engage with correcting the deficient maintenance environment since they now had agency level recognition and support. It had become a priority and the NRC approached the engagement with a two phased approach to be implemented with the MSPP. Phase I was to perform the overall assessment of existing maintenance practices, and their effectiveness, across the industry. Phase II was "to define the role of maintenance in safety, develop recommendations for good practices, and encourage the development of Industry standards."[118] The NRC was, with industry, taking the first steps toward constructing, in their own minds, and in the minds of the industry licensees, what a maintenance technological system should look like and how it could be implemented.

[118] U.S. Nuclear Regulatory Commission 1985, 7.

The View of Maintenance

The NRC assessed plant performance data, gathered from 1980 through 1985, to gain an understanding of how effectively maintenance was performing in keeping plants operating safely and reliably. The data came from several existing sources to include: NUREG-0020, Licensed Operating Reactors - Status Summary Report — which details the number and types of forced plant outages (not generating electricity) due to planned and unplanned equipment outages every month; Licensee Event Reports — where the licensee reports system component defects and failures; Systematic Assessment of Licensee Performance or SALP reports — where the NRC periodically evaluates performance in areas to include not only maintenance/surveillance directly, but also operations, engineering, and plant support.[119] The data were from existing, established NRC sources that had been collected, through the normal processes of reporting, from approximately 80 plants through normal processes of reporting.

For better understanding of the information and presentation of the findings, the assessment team organized the data into five overall categories:

- overall system/component reliability
- overall safety system reliability

[119] U.S. Nuclear Regulatory Commission 1986c.

- challenges to safety systems (RPS and ESF) [Reactor Protection System and Engineered Safety Feature]
- radiological exposure
- regulatory assessment[120]

With this structure to frame the analysis the NRC assessed each performance area as described below:

1) Overall system/component reliability is just that, the entire plant, to include not only the safety-related nuclear SSCs, but also the balance-of-plant (BOP) SSCs. It is the all-encompassing, end-to-end capability of a nuclear power plant to reliably (and safely) generate electricity.

2) Overall safety system reliability is a more specific set of SSCs than that of the overall system. It refers to the reliable functioning of SSCs that ensure or provide for: "(i) The integrity of the reactor coolant pressure boundary, (ii) The capability to shut down the reactor and maintain it in a safe shutdown condition, or (iii) The capability to prevent or mitigate the consequences of accidents which could result in potential offsite radiation exposures. These functions are the nonnegotiable, bottom-line tenets of a safely operating nuclear power plant.

[120] U.S. Nuclear Regulatory Commission 1986c, 4.

3) Challenges to safety systems are, more directly described, inadvertent actions that activate safety systems such the automatic reactor scram that shuts down the reactor. The word challenge is interesting since it is essentially a euphemism for failure to perform maintenance correctly, thus causing the system to react to protect itself.

4) Radiological exposure is an internal look (inside the operational perimeter of the plant) at the doses of radiation that plant personnel receive. In the realm of maintenance, it focuses on how often maintenance is required (generally corrective action) and the duration it takes to complete the maintenance (the longer it takes the greater the potential dose of radiation). A lower exposure could indicate that fewer corrective maintenance actions are performed (less failures) and those that are performed are done efficiently (quickly and correctly).

5) Regulatory assessment is examination of the licensee's regulatory compliance report card. How had the NRC rated the plant operator during regular evaluations? How many major and minor compliance violations had occurred? How many were related to maintenance? This area is a comprehensive performance measure rolled up into a regulatory container.

The NRC's overall assessment findings were mixed: 1) In system/component reliability the NRC found that the trends showed that "there appears to be a significant improvement in the effectiveness of the maintenance departments to provide reliable system and component operation and in their corrective maintenance programs."[121] This was the conclusion after analysis of data recorded over the six years from 1980 through 1985 and included assessment of the number of forced-outages and outages due component failures. 2) By contrast, the assessment of safety system reliability was less encouraging. First, due to unexplained reporting changes, the NRC only used data from two years, 1984 and 1985. In that limited time period, the NRC found that with component failures "both the number and the percentage of those attributable to maintenance error appear to be increasing."[122] Maintenance was causing failures in safety systems, 3) Plant activities were also causing safety systems to be activated. The NRC saw that scram outages had decreased but, "the number of ESF actuations actually increased significantly."[123] ESF is an "engineered safety feature" that automatically activates in response to postulated accidents. For example, if primary feedwater is lost (to cool the reactor) the auxiliary feedwater system (an ESF) is activated in response. Like with safety system availability, the NRC only had two years of data and could not confidently determine which direction the trends were headed; either good or bad, 4) With radiological exposures the NRC did not see a change indicated in the data. They concluded that maintenance methods such as, "maintenance planning practices, scope of preventive maintenance, amount of rework, etc."[124] was managing exposure and, 5) The plant's regulatory report card showed decreases in major and minor compliance violations, but an increase in problems

[121] U.S. Nuclear Regulatory Commission 1986c, 13.
[122] U.S. Nuclear Regulatory Commission 1986c, 13.
[123] U.S. Nuclear Regulatory Commission 1986c, 13.
[124] U.S. Nuclear Regulatory Commission 1986c, 13.

caused by maintenance actions with “both the number and proportion attributed to maintenance increased.”[125] The NRC considered this as due to the recent increased focus on maintenance by both themselves and industry. Overall it is clear that the NRC concluded that the industry’s maintenance technology simply did not adequately exist.

The NRC identified five substantial problems, in regard to maintenance, that were evident across the commercial nuclear power industry. The following abbreviated excerpts from the NRC report, NUREG-1212, *Status of Maintenance in the U. S. Nuclear Power Industry 1985* [126] show the key NRC conclusions concerning the inadequacy of industry maintenance with supporting performance data:

- Needed maintenance is not being accomplished or is not performed effectively.
- An average of 64% of total industry forced outage time is due to component failure.
- Maintenance-related LERs accounted for 39% of industry LERs in 1984 and 48% in 1985. [An LER is a Licensee Event Report, required under 10 CFR 50.73, *Licensee Event Report System.* The licensee reports to the NRC any abnormal event or condition occurring at the plant.]
- A high percentage of failures result from improper performance of maintenance.
- More than 30% of the abnormal occurrences reported to Congress each year since 1975 may be attributable to maintenance.
- The maintenance and operations interface is inadequate.

[125] U.S. Nuclear Regulatory Commission 1986c, 14.
[126] U.S. Nuclear Regulatory Commission 1986a, 1986b.

- A study of 35 instances involving human error in wrong unit and wrong train events showed that operations personnel were frequently at fault In the Incidents (75%), many of which occurred during preparation for maintenance work. Faulty communications between operations and maintenance contributed to wrong unit/wrong train events.

- <u>The number of maintenance-related challenges to safety systems is excessive</u>.

- About 75% of the industry engineered safety features actuations reported during 1984 and 1985 were attributed to maintenance, surveillance and component failures.

- <u>The major portion of occupational radiation exposure and many radiological hazards occur to personnel performing maintenance activities</u>.

- Maintenance-related radiological exposures represented about 46% of total exposures in 1984.[127]

What is legible, concerning maintenance, as framed in the NRC's conclusion? From the data, they observed maintenance as either *not being performed*, and causing or contributing to system failures, or, *being performed*, but *incorrectly*, also causing or contributing to system failures. Absence of maintenance or bad maintenance (preventive and/or corrective) was the *initiating event* for nearly two-thirds of component failures that forced system outages and stopped power production. In the words of Lee Vinsel, "Maintenance breaks things" (personal conversation 22 September 2018). Even more significant, than maintenance caused plant outages, were the safety system actuations related to maintenance. Here, maintenance was dramatically increasing operating risks and compromising safety by putting nuclear plants in hazardous conditions; maintenance was triggering systems designed to prevent

[127] U.S. Nuclear Regulatory Commission 1986a, 16-17.

catastrophic failures. Additionally, maintenance was not only ineffectively (and dangerously) interacting with the machinery of the power plant, but also with the other internal organizations. Maintenance is also organizational communications and interpersonal skills and they were not functioning well with Operations. Furthermore, since maintenance contributed to nearly one-third of failures, that may or may not have led to outages, it is apparent that poor maintenance (by omission or commission), was always lurking in the background and causing problems. Finally, that background presence also carried the unseen, but very real, radiation exposure to the maintenance technicians themselves. The NRC had inspected the plants (or the data representing them) and had found a faulty component or, at worst, a missing one. Maintenance as a technology, a devised way of doing things, constructed of skill, training, technique and culture, was not working properly as a critical technological component of the nuclear plants. It did not meet specifications, was incorrectly installed, ineptly used, or entirely missing, as often is the case with preventive maintenance. Maintenance was breaking things and it needed to be fixed.

Policy and Intent

In April 1987 the NRC staff began development, at the direction of the Commission, of a Policy Statement "to formalize the Commission's position on maintenance."[128] At the end of December 1987, Victor Stello, the Executive Director of Operations, provided

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[128] U.S. Nuclear Regulatory Commission 1987, 1.

the Commission with an interim policy statement for a sixty day review. It was direct in its position: “The underlying philosophy of the proposed Policy Statement is that corrective, preventive and predictive maintenance should be conducted on all plant equipment.”[129] The policy defined maintenance as:

> [T]he aggregate of those functions aimed at preserving or restoring safety, reliability, and availability of plant structures, systems, and components. As such, maintenance includes not only activities traditionally associated with identifying and correcting actual or potential degraded conditions, i.e., repair, surveillance, diagnostic examinations, and. preventive measures; but extends to include all supporting functions for the conduct of these activities.[130]

This definition explicitly went beyond the simple run-to-failure tradition of the nuclear industry's adopted fossil-fuel plant mentality. The policy position was making it clear to industry that the NRC was reworking maintenance. Maintenance was now to be something that would touch every component of a plant from hardware structures to organizational structures. At a public meeting on 07 January 1988, the NRC made their position officially known to industry and others. The NRC published the final policy statement on 23 March 1988.

In the final policy the definition of maintenance remained unchanged. The NRC also used the statement to give notice to the industry that rulemaking was underway because, “[t]he Commission believes safety can be enhanced by improving the

[129] U.S. Nuclear Regulatory Commission 1987, 1.
[130] U.S. Nuclear Regulatory Commission 1987, Page 3 of enclosed policy.

effectiveness of maintenance programs throughout the nuclear industry."[131] Even with the call to *improve* maintenance programs, the NRC was obviously quite aware that most licensees did not have programs that would fit the definition of maintenance. Their policy statement stated, "each licensee should develop and implement a maintenance program which provides for the periodic evaluation, and prompt repair of plant components, systems and structures to ensure their availability."[132] The NRC went on to tell industry that they would soon publish a proposed rule to "establish basic requirements for plant maintenance programs" and that "consideration would also be given to industry-wide efforts that already have been initiated" and "[we] encourage interested parties to provide their views on his important subject."[133] The NRC was giving notice on the inevitable, but asking industry to be part of the reworking of that foregone conclusion.

Mayflower Meeting

In July 1988, at the Mayflower Hotel in Washington D.C., the NRC brought in representatives from the nuclear power industry and the reactor licensees where they were informed that a maintenance rule would be promulgated, as had been practically stated in the policy statement. While there was space for discussion of the details there was no room for debate over whether or not the rule would be finalized and enforced. Victor Stello, NRC Executive Director for Operations, made that clear in his opening

[131] U.S. Nuclear Regulatory Commission 1988c, 9430.
[132] U.S. Nuclear Regulatory Commission 1988c, 9430.
[133] U.S. Nuclear Regulatory Commission 1988c, 9431.

remarks, “Let me emphasize that we are not here to discuss whether or not there will be a rule. That decision has been made. Rather, what is on the table for discussion at this Workshop is how best to address maintenance in a regulatory structure that will improve the effectiveness of maintenance programs.”[134] With that approach the NRC did come to the working group with some options for discussion.

Since the Maintenance Surveillance Program Plan had been active since 1985 the industry and licensees were well aware of the NRC’s focus on maintenance. They had therefore been engaged with their own initiatives to improve maintenance and, the NRC knew this. To take advantage of the industry’s early engagement with improving maintenance the NRC went into the Mayflower working group with five options. Each option framed what the eventual maintenance rule could look like. The options booked ended a compliance spectrum that went from a performance-based rule (Option 1) to a prescriptive rule (Option 5). Option 1 would allow the license to determine how they should perform maintenance to meet rule requirements, while, at the other end of the spectrum, Option 5 would prescribe, in detail, how the licensee should perform maintenance to achieve rule requirements. The NRC wanted the industry’s direct participation in designing the rule and to allow opportunity to utilize existing industry developed maintenance activities if at all possible. Just a month prior to the Mayflower meeting, the Commissioners, in a 17 June 1988 memorandum to Victor Stello, directed the NRC to expedite the proceedings. They knew that five options would be presented

[134] U.S. Nuclear Regulatory Commission 1988d, 1.2.

at the workshop (although they did not apparently know the description of each) and wished to move the discussion along. In the memo, Samuel Chilk, Commission Secretary, told Stello that:

> The Commission believes that In order for the workshop to have a maximum chance of success, the "preferred option" should be defined at the outset. Therefore, staff should develop a "strawman" which would present…the "preferred option" at the workshop.[135]

Chilk informed Stello and the Staff that the Commission's "current preferred option is a rule, limited in scope, which would require that licensees track certain defined maintenance performance indicators (PIs) which would assure the effectiveness of a broad range of maintenance activities."[136] The limited scope characteristic certainly showed that the Commission's preference was weighted toward a performance based rule. Just days later on 27 June 1988, Stello and the Staff responded to the Commissioners and described Option 1 as having the following characteristics:

- Should not divert or hinder good Industry initiatives directed toward improving maintenance:
  - maintain/promote industry responsibility (ownership) for problem identification, resolution and monitoring
  - state objectives, not prescribe solutions.
- Should not require submission of documents or Information that NRC does not plan to review.

[135] Chilk 1988, 1.
[136] Chilk 1988, 1.

- Should have provision to measure overall program effectiveness and ensure feedback of results to improve the program.[137]

The NRC walked into the Mayflower Hotel in July 1988 and presented the five options to the 300 participants from the nuclear industry. They advocated for Option 1, the framework for a performance-based rule, and emphasized its advantages to industry and the licensees. It had inherent flexibility to allow the licensees to utilize any existing well performing maintenance practices and it simplified regulatory actions for the NRC. At the conclusion of the workshop, Option 1 was adopted by the NRC staff where they (Stello) concluded in a memo to the Commission:

i) Rulemaking should encourage industry initiatives directed toward improving maintenance, since such initiatives promote industry responsibility for problem Identification and resolution;
ii) Prescriptive rulemaking options may impede industry initiatives and responsibility to improve maintenance; and
iii) Rulemaking should be directed toward specifying the NRC's expectations in maintenance and require monitoring of the effectiveness of maintenance programs, although at the present time the staff Is not prepared to recommend a uniform set of maintenance performance indicators (NPIs).[138]

The NRC preferred a rule that was general enough for the licensees to develop a maintenance standard and allow for the NRC to endorse the standard in a Regulatory Guide. The licensees would be required by the rule "to have and implement a

[137] Stello 1988b, 5.
[138] Stello 1988a, 2.

documented maintenance program" where "compliance with the rule would be verified by NRC audit and inspection."[139] The licensees at each plant could locally construct their maintenance programs and the NRC could lighten its hand of oversight on specific details and focus on overall performance compliance. The licensees would ultimately have to comply with the law of the Maintenance Rule, and maintain safe and reliable power plants, but how they accomplished that was within their agency. The NRC wanted the industry to tell them what they were going to do and show them how they were doing it. The next step was for the NRC to determine how they were going to implement the rule.

Conclusion

What did we see happening in the decade after the TMI-2 accident and three decades after the first U.S. commercial reactor began to produce electricity? We saw the beginnings of reconstruction of maintenance thinking due, in part, by the near catastrophe of TMI-2. Maintenance thought and activities began to move away from being primarily reactive tasks to a proactive system of integrated activities. The maintenance initiated TMI-2 accident was a near fatal blow to the body of the commercial nuclear industry, but while it was a severe hit, response from the NRC and the industry was not reflexive with respect to nuclear system maintenance. Instead of a sudden jump to plan for the repair of a failed maintenance system, prompted by a reactor meltdown, there was a slow, gradual progression toward that end. The

[139] Stello 1988a, 3.

extensive and multiple investigations looked at many aspects of the accident and this included maintenance. As I have shown, while maintenance was not ignored it was not fully engaged with by any of the investigators except the engineers.

I would describe it as maintenance being carried along with the investigations, but not identified as a failed critical system. It appears that the investigators did not recognize nuclear maintenance as a complex system in itself and were still treating it as a task-specific activity in the same manner as it had been treated since the beginning of commercial nuclear power. Therefore, they did not write high-priority recommendations for maintenance program development into their accident reports. Here is evidence that the government and industry investigators were still viewing a nuclear-fueled electric power plant as, what I discussed in Chapter 1, "normal technology"[140] built with "normal design"[141] ideas and knowledge. The maintenance thinking, of those in the nuclear power community, remained in the realm of the well-known technology of fossil fueled power plants.

It took the NRC's normal administrative policy improvement efforts to stimulate the development of the Maintenance Program Plan. The MPP effort, in turn, prompted a relook at the TMI-2 accident reports where the stand-alone maintenance task failures were used as indicators to support the need for a nuclear maintenance program. What we see is the combination of a receptive regulatory environment, with active processes, working with TMI-2 accident information to initiate creation of the Maintenance Rule. Implementation of the Rule was the next, non-trivial, step.

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[140] Constant 1980, 10.
[141] Vincenti 1990, 7.

Chapter 4
Implementation of the Maintenance Rule

This chapter looks at how the NRC and the nuclear industry practically implemented the Maintenance Rule to take effect at over 60 nuclear power plants, operating over 100 reactors, and being maintained by thousands of personnel. I follow the government regulatory rule making path of the NRC as the process frames and guides government and industry actions. The process was extraordinarily visible to the public with rule proposals and the final rule published in the U.S. Federal Register. The Register also often included background discussions between the NRC, industry and others. Further extensive detail, often referenced in the Register, was available in the NRC's Public Document Room (PDR) and included voluminous information such as hearing transcripts. The workings of the implementation of the Maintenance Rule were clearly visible and also legible to those who studied the documents.

In the following narrative, I begin with a study of the Maintenance Rule development sequence by examining the negotiation, construction, and finalization of the rule by the NRC and industry. The final rule covered less than two pages in the Federal Register and I explore why it was written to be so succinct. I then dive into detailed looks at the two documents that take the Rules performance requirements and implement them; the industry's maintenance guideline and the NRC's endorsing regulatory guide for implementation procedures of the Maintenance Rule. Finally, I observe how the NRC and industry evaluated the Rule in the working commercial nuclear power plant environment with both an early test program and fully functional operational assessments. Implementation of the Maintenance Rule was an eight-year journey spanning from 1988, when the proposed rule was published, to 1996 when the rule was to be fully implemented by the commercial nuclear power industry.

Proposed Rulemaking

In late 1988, the NRC kicked-off implementation of the maintenance rule after nearly a decade of internal planning and discussion, and subsequent contemplation with the nuclear industry. Following the extensive Mayflower Hotel working group discussions, the NRC built, as per the process of the Administrative Procedure Act (APA), a full-scale mock-up of the maintenance rule and rolled it out of the regulatory hanger. This mock-up was the prototype rule for industry and the public to walk around and examine. It was also a planning artifact that the NRC itself was to use to develop a regulatory guide to fly, or implement, the rule once finalized. The proposed design documented the objective of the rule itself and also summarized the working path of discussions that culminated in the proposal.

The maintenance rule was proposed by the NRC to be implemented as a fundamental technical artifact of safety:

The Commission believes safety can and must be enhanced by strengthening the effectiveness of maintenance programs throughout the nuclear industry and this is the objective of the proposed rule.[142]

The NRC directly connected maintaining safety to maintaining a nuclear plant's systems, structures and components (SSC). Safety was assumed to be inherent in the normal, or as engineered, operations of the SSCs that compromised a nuclear power plant, therefore; the purpose of effective maintenance was to ensure that the myriad of "plant equipment will perform its intended function when required."[143] On commands from human operators or system interactions, valves had to open and close, pumps had to move coolant, relays had to energize and deenergize, instruments had to provide accurate and trustworthy readings; all without failure. Everything had to safely and reliably work as designed and built; as the equipment manufacturers advertised in their specification sheets.

The NRC's path toward implementation connected groups of activities that were broadly framed by the APA rule development public process and the nuclear industry's and the NRC's common practice of developing rule implementation standards and guidelines in parallel. There were five sets of primary tasks and of information sharing:

1) Publication of a proposed rule based upon historical assessment of maintenance and preliminary discussions among the government and the nuclear industry
2) Review and comment on the proposed rule by nuclear industry and the public
3) Construction of the final rule
4) Development of a maintenance standard by the nuclear industry

142 U.S. Nuclear Regulatory Commission 1988b, 47823.
143 U.S. Nuclear Regulatory Commission 1988b, 47823.

5) Development of a regulatory guide that would endorse the industry's maintenance standard by the NRC

In the frame of the Federal Register, the NRC described the outcome of their thinking that shaped the proposal. The NRC came to the conclusion that effective maintenance is the product of a carefully constructed program as comprehended and executed by its practitioners. Maintenance could not simply be composed of ad hoc individual tasks only initiated upon discovery of component failures. The program would specifically define systems, components, and structures and the preventive maintenance and surveillance required to ensure they remained functional. Dedicated management systems, implemented by the licensee, would administer and control maintenance activities and set and enforce standards. Also fundamental to the maintenance program would be implementation of trend and root cause analysis to trace problems to potential operational use errors and fundamental engineering design faults.

Significantly, maintenance actions would not only cover those SSCs directly related to the functioning of the nuclear areas of a plant, but those secondary areas, or the balance of plant (BOP), that could potentially affect the overall safe functioning of SSCs. The condensate polisher at TMI-2 was a just such a BOP component. Finally, the NRC informed the nuclear plant licensees that their maintenance effectiveness management and monitoring methods, whatever they devised, would be under NRC review.

The NRC made it clear that the primary outcome of the Mayflower Workshop discussions, with industry, was the shaping of a fundamental regulatory approach toward implementation of the maintenance rule. The NRC decided that purely prescriptive government direction would inhibit industry from using its own locally developed initiatives. The NRC also felt that explicit direction would also drastically reduce industry's initiative and responsibility for safe and reliable plant operation through locally constructed maintenance programs. The NRC stated that the intent of their rulemaking "should be directed toward specifying the NRC's expectations in maintenance and requiring licensee monitoring of the effectiveness of maintenance programs."[144] With that the NRC summarized that their proposed rule "gives incentive for industry to develop a standard for a maintenance program, which the NRC may endorse in a Regulatory Guide."[145]

The Commission provided further incentive by outlining its plan to develop a Regulatory Guide for issuance in November 1989. The NRC told industry it would work the guide "in parallel with the final rulemaking…[and] encourages the industry to develop standards…[and] if an acceptable industry standard is available in this time frame, the Commission will consider endorsing the industry standards in the Regulatory Guide."[146] The NRC was rather subtly saying, "We're writing a reg guide and you, industry, have an opportunity to shape it". They were instituting a top-down approach, but the NRC thought a lighter weight top would be less likely to squash industry initiative

[144] U.S. Nuclear Regulatory Commission 1988b, 47823.
[145] U.S. Nuclear Regulatory Commission 1988b, 47823.
[146] U.S. Nuclear Regulatory Commission 1988b, 47824.

and be more effective (and more likely) in gaining industry acceptance, participation, and the necessary actions to develop maintenance programs.

The NRC, while not applying an obvious heavy hand, (the Commission often used the word “encourages” rather than “directs” when referring to actions it wanted the industry to take) it was not reticent in spelling out that it wished the nuclear industry to develop a maintenance standard and one that met several requirements. First, the standard had to define the SSCs of the maintenance program and, again, include those SSCs existing in the BOP. Second, the standard should be constructed using a “systems approach”[147] or systems-thinking methodology[148] so that maintenance requirements are evaluated and integrated across the plant. Third, maintenance had to be implemented and managed programmatically to ensure comprehensiveness and reliability. Fourth, the standard should use and build upon applicable engineering and industry standards such as those from ASME, IEEE, INPO and EPRI. Fifth, the NRC required that an output of a maintenance program not be effective maintenance and safe and reliable operations, but documentation so the NRC could evaluate rule compliance by industry. Finally, interestingly, the NRC also stated that they had assessed and reported how other industries and countries had implemented maintenance programs.

As part of the industry and public review of the proposed rule, they requested comment on their report NUREG-1333, Maintenance Approaches and Practices in Selected Foreign Nuclear Power Programs and Other U.S. Industries: Review and

[147] U.S. Nuclear Regulatory Commission 1988b, 47823.
[148] Bertalanffy 1969.

Lessons Learned.[149] Here we see that while the NRC used a reasonably light regulatory touch they did not wish that the U.S. nuclear industry create a maintenance standard unguided and within a technological vacuum. Further, in this respect, they also not so lightly prodded the industry with rather unfavorable public comparison of their competency with foreign peers and parallel industries. They considered this comparison significant enough to call explicitly call out several practices they felt "contribute significantly to effective maintenance."[150]

The NRC's Office of Nuclear Regulatory Research (ONRR) examined the commercial nuclear power plant maintenance programs as implemented by Japan, France and West Germany. The ONRR also looked at how the U.S. Federal Aviation Agency (FAA) regulated commercial aviation maintenance and how it was carried out by the airlines. They further examined U.S. Air Force and Navy military aircraft maintenance programs. All of these programs required effectively structured and managed programs to ensure the safe and reliable operations of their complex and often hazardous systems. With this study the ONRR summarized its findings, in NUREG-1333, *Maintenance Approaches and Practices in Selected Foreign Nuclear Power Programs and Other U.S. Industries: Review and Lessons Learned,*[151] by identifying eight areas of critical maintenance practices: 1) A maintenance program should be proactive in nature. It should focus on preventive maintenance actions and not be prone to running systems to failure, 2) a reliability-centered maintenance

[149] U.S. Nuclear Regulatory Commission 1988b.
[150] U.S. Nuclear Regulatory Commission 1988b, 47824.
[151] U.S. Nuclear Regulatory Commission 1990.

strategy that determines and establishes a minimum safe, or optimum, level of maintenance required to sustain functional reliability and safety, 3) formal failure data collection and analysis to determine root-causes of the failures, 4) an information system to record and manage maintenance data, 5) formal training for maintenance technicians, 6) use of maintenance program objectives to drive maintenance planning and execution, 7) emphasis on the importance of maintenance technician skills and their critical importance in plant functioning, and, 8) well-structured and understood integration between maintenance activities and all other plant activities, especially operations.

From my own maintenance experience, with aircraft weapons systems, I see these practices as fundamental; they are basic tenants of practical, effective, and mature maintenance programs. It is a telling assessment of the quality of commercial nuclear maintenance for the NRC to present these in a public forum. While the general public may not be aware of the nuances of reliability-centered maintenance or scheduling, they would surely understand, for example, the importance of preventive maintenance and, most critically, the training of maintenance personnel.

As a normal part of the public examination of a proposed rule, overall questions and comments are solicited by the government from the affected parties and the public. The NRC also asked for responses to several specific questions. Somewhat surprisingly, after spending considerable time describing how the nuclear industry should develop a maintenance standard the NRC then directly asks the industry, "Is it appropriate for the nuclear power industry to develop a Maintenance Standard and, if so, would the industry develop such a Maintenance Standard?"[152] They also asked industry how detailed should a maintenance standard be and if two years (the timeline the NRC recommended) was sufficient time for implementation. Furthermore, the NRC inquired whether it was "appropriate for a designated third party to certify plant maintenance to comply with the Maintenance Standard; and, if so, would an organization be willing to perform such certification?"[153] Additionally, the NRC, while "[believing]…inclusion of…BOP equipment…is necessary and proper" questioned the absolute scope of the proposed maintenance rule concerning BOP SSC applicability.[154]

The Commission pointed out to the public that some licensee maintenance programs applied to SSCs "that are, without question, irrelevant to protection of public health and safety from radiological hazards."[155] With that observation the NRC then questioned the public directly. Did they feel having these non-safety related items in the scope of the proposed maintenance standard was important to them? In other words, would it bother them if the operator of their local nuclear power plant had some latitude in how it defined its maintenance requirements? Next, related to maintenance technician training, the Commission stated it thought that worker accountability was important and asked how it might be added to a licensee's maintenance program. The Commission also asked the public a broadly fundamental question; how should we know when a maintenance program is effective enough "and additional improvement is not warranted from a safety standpoint" and what criteria should be utilized to determine

[152] U.S. Nuclear Regulatory Commission 1988b, 47824.
[153] U.S. Nuclear Regulatory Commission 1988b, 47824.
[154] U.S. Nuclear Regulatory Commission 1988b, 47825.
[155] U.S. Nuclear Regulatory Commission 1988b, 47825.

it?[156] Again, would citizens reach a point under the proposed maintenance rule to feel that their local nuclear power plant was maintained enough to be safe enough? Tentatively, would be my one word description of how the NRC was seeming to approach implementation of the maintenance rule. As the process of proposing is designed to do, they were getting a feel for the reaction of the nuclear community to include the public, but they were also making every effort to not be, and not appear to be, prescriptive. In stark contrast the views of Commissioner Thomas Roberts were far from tentative and encouraging.

The text of the rule proposal also included dissenting comments from Commissioner Roberts. He opened his comments with, "I cannot join the majority in supporting the proposed rulemaking on maintenance."[157] Roberts asked, "What are we trying to accomplish with this rule that cannot more effectively and innovatively be accomplished without a regulation?"[158] He did not believe that the plant licensees did not already have established and enforceable maintenance programs and was not convinced that additional regulation would further improve them. Roberts' most significant criticism was his quoting the view of the Advisory Committee on Reactor Safeguards (ACRS):

> [T]here are characteristics of regulations, and especially the way in which they are typically enforced, that lead us to believe that, under a rule, a move toward uniformity would occur, and this is likely to decrease the effectiveness of some of the better existing programs.[159]

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[156] U.S. Nuclear Regulatory Commission 1988b, 47825.
[157] U.S. Nuclear Regulatory Commission 1988b, 47825.
[158] U.S. Nuclear Regulatory Commission 1988b, 47825.
[159] U.S. Nuclear Regulatory Commission 1988b, 47825.

Roberts concluded by stating he thought effective maintenance was necessary for safe nuclear plant operations for the protection of the public, but he emphasized, "that *this rule is not necessary to provide that protection*, and that as the ACRS noted it may well have the opposite effect"[160] [emphasis in original].

The Proposed Maintenance Rule - 28 November 1988

The proposed rule itself, designated "§50.65 Requirements to ensure the effectiveness of maintenance programs for nuclear power plants" was contained in 10 CFR Part 50 — Domestic Licensing of Production and Utilization Facilities, and was laid out in less than two-thirds of a page.[161] The previously examined background and discussion of the rule covered over six pages in small print. With this lengthy narrative, the NRC formally, and publicly, engaged with the nuclear industry and the public to build the maintenance rule. In the context of the NRC's rulemaking, the maintenance rule's implementation also involved its joint construction by the NRC and the nuclear power plant licensees. Their starting point was the proposed rule artifact and several defining and descriptive characteristics:

- It explicitly defined maintenance
- It described maintenance in programmatic terms
- It specifically identified maintenance technical and management activities

[160] U.S. Nuclear Regulatory Commission 1988b, 47825.
[161] U.S. Nuclear Regulatory Commission 1988b, 47828.

- It required nuclear power plant licensees to establish and maintain a maintenance program and regularly assess its effectiveness in order to make improvements
- It set a rule implementation timeline for the licensees of two years after publication of the final rule[162]

I see the rule as not intended to arrive on the floors of commercial power plants as a complete and tested component of regulatory technology. Its preliminary form was shaped by these attributes and they provided the rule builders a basic and explicitly legible framework for final rule construction.

Development of the Proposed Rule

After the NRC officially exposed their mocked-up Maintenance Rule to the public for comment, they made several changes to the rule in response to the commentary. The NRC generally summarized their changes as being ones that clarified, and made more explicit, the intent and the functioning of the rule. First, they changed the Maintenance Rule title from "Requirements to ensure the effectiveness of maintenance programs for nuclear power plants"[163] to, "Requirements for maintenance programs of nuclear power plants."[164] Here, the NRC explained that the change was to better "reflect the purpose of the rule…"[165] Paradoxically, if we take the new title at its

[162] U.S. Nuclear Regulatory Commission 1988b.
[163] U.S. Nuclear Regulatory Commission 1988b, 47828.
[164] Stello 1989, Page 1 of Enclosure 3.
[165] Stello 1989, Page 1 of Attachment to Enclosure A.

face value it describes the rule's purpose less explicitly than the former title. The new title shifts from mandating effective maintenance programs to merely requiring maintenance programs, without defining their quality. Interestingly, in the NRC's introductory document, for the proposed rule, the NRC explicitly states that their intent is to "sustain good performing programs."[166] Second, the NRC wished to clarify the meaning of degraded conditions that were called out in the proposed rule. With the change they went on to specify that the source of degraded plant conditions were "due to environment and service over time, or other causes."[167] Rather ironically, this NRC clarification itself provided some ambiguity. They added, but did not explicitly define, "other causes" in their clarified rule. Like with the title, the new clarified definition was included in the SECY document where the NRC explained these indeterminate causes by giving as an example, "human error"[168] as something that also could degrade system functioning. Third, the NRC further defined the scope of the SSCs covered by the Maintenance Rule. They stated that, "the maintenance program shall include structures, systems, and components whose failure could significantly affect the safety or security of the facility."[169] This explicitly coupled the potential failure of SSC's with their subsequent effect on the operational safety and security of the plant. Fourth, the NRC more directly brought maintenance programs themselves under the eye of the Maintenance Rule. Rather than requiring licensees to assess the effectiveness of their maintenance programs and "make improvements" the NRC ordered the licensees

[166] Stello 1989, Page 3 of Enclosure A.
[167] Stello 1989, Page 3 of Enclosure A.
[168] Stello 1989, Page 3 of Enclosure A.
[169] Stello 1989, Page 3 of Enclosure A.

to assess and "plan and execute corrective actions."[170] They use the same language that they used to describe maintenance activities and here the language implies that maintenance programs, like SSCs, can fail and explicitly requires action to repair them. Here, I see maintenance being shaped and formally constructed as a critical system or component of a nuclear power plant. Finally, to facilitate implementation of licensee compliance with the new 50.65 Maintenance Rule the NRC added an option that the licensees could establish compliance utilizing third-party certification of the maintenance programs. The NRC was giving the industry an option for easier, or more effective, implementation of the Maintenance Rule. In all, with these changes, the NRC was actively and publicly responding to concerns and recommendations; they were, for all practical purposes, negotiating with the U.S. commercial nuclear industry.

While the industry was legally obligated to follow the Maintenance Rule once it was finalized into law, the NRC was pushing to construct something that the industry would accept with at least a modicum interest and, better yet, something they participated in creating. For the Maintenance Rule to be truly effective the industry had to be on-board. The NRC and the nuclear industry were still finding their mutual footing to make this happen.

Publication of Draft Regulatory Guide - 17 August 1989

With industry and even some in the NRC restless and grumbling about the necessity or even the safety of the maintenance rule, the NRC's Office of Nuclear

[170] Stello 1989, Page 3 of Enclosure A.

Regulatory Research pressed ahead and developed a regulatory guide. This described what the NRC perceived as what an effective maintenance program should look like. The draft guide, with the working designation of “Task DG-1001” constructed a comprehensive maintenance program framework.[171]

The guide opened with a direct statement that said the NRC had “amended its regulations in 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities, “to clarify and extend previously existing Commission requirements for maintenance programs of nuclear power plants, both explicit and implicit.”[172] The NRC was working to eliminate any ambiguity found in their previous descriptions of the requirement for the nuclear industry to perform maintenance. Furthermore, the NRC explicitly coupled formalized and systematic maintenance with the mandate of the Atomic Energy Act of 1954 and their own mission statement to ensure that the public’s health and safety is protected from radioactive materials. They stated that, “Safe operation of a nuclear power plant is directly dependent on the scope, depth, and quality of a plant’s maintenance program.”[173] In DG-001, the NRC told the nuclear industry just what they considered as the breadth, level of detail, and to what performance, a maintenance program was required to function as a component system of a nuclear power plant.

[171] Stello 1989, Enclosure B.
[172] Stello 1989, Page 1 of Enclosure B.
[173] Stello 1989, Page 2 of Enclosure B.

Scope – What is included

A nuclear power plant is an extraordinarily complex system of machinery, high temperatures, pressures, and voltages, with hundreds of associated pumps and valves and miles of piping transporting superheated steam and cooling water. All of this is connected by miles of electrical cabling, and thousands of circuits that carefully control a steel and concrete contained fission reaction emitting lethal radiation.. These systems, structures, and components are broadly categorized into two large system areas: the nuclear steam supply system (NSSS) and the balance-of-plant (BOP). The NSSS is the nuclear portion of the plant and consists of the reactor itself, its core coolant and emergency cooling systems, and the various reactor pressure control systems. The BOP are the steam turbines, electrical generators, condenser system, the demineralizer and feedwater systems.[174] All are coupled together and virtually all are required (or potentially required as redundant backup systems) to operate as designed to safely generate nuclear power.

It was this system of systems, in its entirety, that the NRC was requiring the plant licensees to effectively maintain to ensure safety. The regulatory guide explicitly defined maintenance, for the industry, as “the aggregate of those planned and systematic actions required to prevent the degradation or failure of, and to properly restore the intended function of structures, systems, and components. This applies to all

[174] Lamarsh and Baratta 2001.

parts of the plant that could significantly impact safe operation and security, including the BOP."[175]

The guide's calling out of the BOP as being in scope of mandatory maintenance was most significant, but not surprising since the initiating event at TMI-2 was attributed to the condensate polisher in the BOP. The nuclear industry was put on notice that it had to evaluate every SSC of the plant to determine its safety significance and apply appropriate maintenance actions as planned and managed in a formal maintenance program.

Depth - Level of detail

The NRC was requiring that a plant's maintenance activities had to be much deeper than only repairing things that became apparent when they failed. They emphasized that, "Fundamentally, the maintenance program should minimize corrective maintenance, to the extent practical, and should rely on sound preventive and predictive maintenance."[176] If corrective maintenance actions were, for all intents and purposes, programmed at the time component failure became visible to plant operators then preventive and predictive maintenance would require a much more prescient system; that is what the NRC described in the definition of the working extent of a maintenance program.

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[175] Stello 1989, Page 2 of Enclosure B.
[176] Stello 1989, Page 3 of Enclosure B.

An effective maintenance program involves a systematic approach whereby overall policy, goals, and objectives are established: the effectiveness of maintenance is monitored and assessed, and, based on the monitoring and assessment activities, timely feedback and corrective actions are executed. Incorporating these steps in the maintenance program is considered essential to ensuring that an effective maintenance program is achieved and maintained.[177]

A maintenance program would formally structure and plan maintenance execution. That execution would be based upon objectives and goals that were to be locally determined by each plant licensee with it being "the responsibility of senior management to establish the standards and policies for the organization, oversee implementation, and assess the effectiveness of its maintenance program."[178]

The NRC emphasized that, for an effective and locally accepted and adopted maintenance program, the licensee was to construct goals and objectives. The fundamental objective was clearly legible in the proposed 10 CFR 50.65 and called out again in the NRC's Guide. The objective, the overarching strategic position, of the nuclear enterprise's maintenance program was to "prevent the degradation or failure of, and to promptly restore the intended function of, structures, systems, and components."[179] Utilizing their maintenance program the nuclear licensee was to ensure that the plant SSCs were reliably performing at any given time and, also, that any variations in performance were not trending toward continued degradation and failure. Of course, variations of performance are only legible if they are measured relative to standard references or "quantitative goals."[180] Here, the NRC stated that

[177] Stello 1989, Page 4 of Enclosure B.
[178] Stello 1989, Page 5 of Enclosure B.
[179] Stello 1989, Page 6 Enclosure B.
[180] Stello 1989, Page 6 of Enclosure B.

“goals should be directed toward improving or sustaining equipment reliability and performance due to maintenance effectiveness in areas key to plant safety and risk.”[181]

The goals, the desired SSC conditions, were the numbers representing optimal SSC functioning such as gallons of coolant flow per minute, voltage loads, insulation resistance, vibration frequencies, pressures, generator startup times, availability, redundancy, trending, and the probabilistic risk assessments (PRA) of potential failures.[182] Furthermore, while the NRC understood that each plant was practically distinct in its construction and operation, they expected the goals to be, if not harmonized, at least generally known and shared across the commercial enterprise: “In general, goals should be established with the objective of achieving a level of performance consistent with that achieved by the top performing U.S. plants of similar design.”[183] Here was NRC’s call for the industry to share common operating experience or OE.

A decade earlier, during the TMI-2 accident investigation, the NRC recognized the potential consequences of not effectively sharing OE. They discovered that the Davis Besse nuclear plant had encountered, and recovered from, nearly the same accident sequence (involving both maintenance and operations) that had occurred at TMI-2, but that information was not shared within the nuclear community. Here we see the NRC stressing that information is a key component of an effective maintenance program and in successfully meeting the program’s objectives and goals. Information is a primary

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[181] Stello 1989, page 6 of Enclosure B.
[182] For a thorough historical examination of PRA in the nuclear power industry see Thomas Wellock’s article, “A Figure of Merit”, in Technology and Culture (Wellock 2017).
[183] Stello 1989, page 7 of Enclosure B.

creation and output of the various types of maintenance activities, but if it is not shared it is of little use beyond the local organization and can, (and did) have catastrophic consequences.

In the maintenance guide the NRC described three types of maintenance that "should be developed by each licensee consistent with meeting…established goals and objectives:" corrective, preventive, and predictive, maintenance.[184] Corrective maintenance was "break fix"; repair action taken after an SSC had failed, to return it to service. This after-the-failure type action was historically what the commercial power industry employed and it typically defined maintenance overall. Intentionally planned maintenance downtime was not viewed as cost effective by the commercial power industry, so the system was run to maintenance or, as we have heard, run to failure.

An SSC requiring corrective maintenance was a device with unknown functional capability until it failed, *and* potentially unknown functional status until the failure was *recognized* by the plant operators. The safe operation of the plant was degraded by these unknowns. The NRC was driving to make corrective action the exception rather than the rule by requiring the generation of maintenance information, *by* the maintenance program, that would inform the maintenance program itself. For corrective maintenance, that information was to be created by formal and documented root-cause analysis of the malfunction; information that would "feedback into the preventive and predictive maintenance programs and maintenance training and qualification

[184] Stello 1989, Page 13 of Enclosure B.

program."[185] It was preventive and predictive maintenance that were to form the core and be the driver of an effective maintenance program.

For the NRC, preventive maintenance was a critical component of a safely functioning nuclear power plant. The NRC described preventive maintenance as "[consisting] of all those systematically planned and scheduled actions performed for the purpose of preventing equipment failure" and it was the failures that the NRC was posturing itself and the industry to prevent and to reduce.[186] The preventive maintenance activities contained the information required to know, understand, and respond to the equipment to keep it from failing. It constructed what should be done to an SSC, to verify and ensure its proper functioning, and how often it should be accomplished. This included periodic checks of electrically operated valves to ensure they opened and closed with the required current and voltages and leak checks of seals. Whereas corrective action maintenance is reaction to failure, preventive maintenance is reaction to predictive maintenance. It is designed to identify potentially *pending* failures and to address anomalies to *prevent* ultimate failures. In this environment of maintenance information, preventive maintenance is directly informed and shaped by the findings of predictive maintenance.

Predictive maintenance is the source of information that defines the preventive maintenance activities; the what, and how frequently. It is the monitoring, assessment, analysis and trending of SSC conditions "that indicate the need for preventive

[185] Stello 1989, Page 13 of Enclosure B.
[186] Stello 1989, Page 13 of Enclosure B.

maintenance prior to equipment failure."[187] Initially, predictive maintenance prescribes the appropriate preventive maintenance based upon what fails and how often. Subsequently, with increased operating experience, preventive maintenance progressively identifies leading indicators of failures such as increased vibrations, noise, voltage fluctuations, stress fractures, abnormal pressures and restricted liquid flows. Through continual monitoring, data collection, assessment, root cause and trending analysis of failures that do occur, predictive maintenance builds a knowledge base for planned and executable preventive maintenance activities.

By emphasizing the close information coupling of predictive maintenance with that of preventive maintenance actions, the NRC was moving to enhance plant safety and reliability by shifting the industry's operational view from a run-to-maintenance (run-to-failure) reactive philosophy to, what I would describe as a *run-with-maintenance* philosophy. It was not only the continuous eyes-on and hands-on maintenance activities that the NRC was pushing toward, by means of run-with-maintenance thinking, it was also maintaining the maintenance program itself.

Performance

The NRC described maintenance of the maintenance program as involving licensee surveillance of the maintenance actions themselves and their down-the-line performance outcomes: "The conduct of maintenance activities and their overall

[187] Stello 1989, Page 13 of Enclosure B.

effectiveness should be regularly monitored and assessed."[188] Is maintenance itself being properly performed by the plant maintenance personnel and *not causing* more failures than it was attempting to correct? Ultimately, is maintenance predicting and preventing failures? This internal monitoring program was to be those "methodologies used to perform maintenance surveillance activities and the interfaces with the predictive and corrective maintenance program."[189] The surveillance methodologies were also to have the capability to assess modifications to the plant and to develop and incorporate the appropriate predictive and preventive maintenance activities for the changes. Furthermore, to provide mitigation against potential failures caused by maintenance, corrective maintenance actions were to be formally planned, communicated, and executed with standardized processes and procedures. A key aspect of this mitigation was to employ "Post maintenance testing (PMT)" to ensure that SSCs taken out of service for maintenance were returned to service verified as fully functional "and that the performed maintenance did not affect other functions."[190] Overall, the effectiveness of maintenance was recommended by the NRC to be measured by assessing data on the frequency of component failures, in other words, was predictive maintenance effective in structuring preventive maintenance to prevent component failure and was corrective maintenance correctly performed so as to return a component to service without causing other failures? Finally, the guide described corrective program maintenance much as it did for corrective physical maintenance

[188] Stello 1989, Page 16 of Enclosure B.
[189] Stello 1989, Page 14 of Enclosure B.
[190] Stello 1989, Page 15 of Enclosure B.

where the "corrective action process should determine the cause of the deficiency (administrative, procedural, training, technical etc.) and provide for timely and documented corrective action."[191] Here, root cause analysis and repair were also to be performed on programmatic component failures.

While the maintenance rule defined the general requirements of maintenance, the regulatory guide was the government specification of a maintenance program as a system component of a nuclear power plant. With the guide, the NRC was describing integrated systems thinking[192] [193] by recognizing that maintenance was a coupled system of activities, both physical and logical, that was in turn coupled to all parts (the SSCs) of the nuclear power plant. The maintenance rule was forcing the nuclear industry to construct a safety critical system component, a maintenance program, for their nuclear power plants. The associated regulatory guide was specifying components and systems, their coupling links, interfaces, and feedback loops that provided for self-regulating corrections. By constructing a specification, the NRC was working toward their objective to make the historically implicit maintenance requirements explicit, and usefully legible, across the U.S. commercial nuclear power environment. Examining the NRC's approach, I would argue that they were looking to shift the conception of a nuclear power station from being viewed as a plant to that of a nuclear power system. The word system makes clearer the critical interrelationships among all physical and logical aspects that compose the whole of a nuclear power

[191] Stello 1989, Page 18 of Enclosure B.
[192] Ackoff, Magidson, and Addison 2006.
[193] Bertalanffy 1969.

station. The word plant harkens back to industrial factories with individual pumps, valves, piping, cabling, boilers and generators; where each was generally viewed in isolation and run to failure without significant consideration to how it affected the overall plant. Here was the fossil fuel mentality where nuclear power systems were operated and maintained as the traditional coal, oil and gas fueled power stations. In 1989, the NRC's move to shift from plant to systems thinking, as prodded by the maintenance rule, was unilateral at best.

One sided, because the nuclear industry was not yet on board with active participation. It had not engaged with the NRC's offered opportunity to create its own maintenance rule implementation standard. As we have seen, in the lead up to the creation and publication of the proposed maintenance rule, the NRC encouraged the nuclear industry to develop maintenance standards rather than having the government prescribe standards. They felt if the standards were locally developed by the licensees, who were performing and responsible for the work, then implementation would be more likely to meet the maintenance rule requirements and, therefore, be more effective; the licensee would have buy-in. The NRC informed the industry that they would write a government regulatory guide, but if industry produced, in parallel, their own maintenance guidelines the NRC would use it to inform development of the government guide. Interestingly, the NRC's regulatory guide is not mandatory; only the maintenance rule itself is compulsory since it is law. The regulatory guide describes the recommended, but not all inclusive, maintenance program implementation methods that the NRC would approve to meet maintenance rule requirements. The methods are comprehensive, but fairly general, so as to give licensees “flexibility...for the conduct of specific maintenance activities [and to] tailor their maintenance programs to their specific plant designs and configurations, organizational structure, and personnel.”[194] Overall, this allowable flexibility in implementation was considerable.

While the NRC made it clear that their regulatory guide would be the default standard used to evaluate a licensee’s compliance with the maintenance rule, the non-mandatory nature of the guide gave licensees the option of an “alternative acceptable method” for standards evaluation.[195] It is clear that the NRC was making every effort to make implementation of the maintenance rule as non-prescriptive as possible; non-prescriptive, and thus more palatable for the industry to accept.

Publication of Final Rule - Maintenance Rule 50.65 - 10 July 1991

> It was very elegant. If you look at the maintenance rule it's like a page, right?[196]
>
> - NRC Engineer

On 10 July 1991, the NRC published, as the final rule, *Monitoring the Effectiveness of Maintenance at Nuclear Power Plants*, in the U.S. Federal Register.[197] Maintenance now formally occupied the regulatory environment as 10 CFR 50.65 and was law of the American commercial nuclear power plant land. The Commission stated that they had

[194] Stello 1989, Page 19 of Enclosure B.
[195] Stello 1989, Page 19 of Enclosure B.
[196] Interviewee 008 31 August 2018, Time - 0:24:07.9.
[197] U.S. Nuclear Regulatory Commission 1991.

come to “the conclusion that proper maintenance is essential to plant safety.”[198] To achieve proper maintenance the new law mandated that plant licensees have in place effective maintenance programs and that they continually *knew* that their programs were performing effectively. The rule described two objectives: 1) A focus on ensuring that safety related structures, systems and components (SSCs) were always in condition to perform their design functions, 2) a focus on ensuring that “for non-safety related equipment, failures will not occur which will prevent the fulfillment of safety related functions.”[199] To reach the objectives, the Maintenance Rule prescribed methods to assure maintenance effectiveness and described the intended workings of both in accompanying material published in the Federal Register.

The rule mandated two implementation approaches: First, in paragraph (a)(1) of 50.65, the NRC required that, “the licensee establish a monitoring regime which is sufficient in scope to provide reasonable assurance that…intended safety, accident mitigation and transient mitigation functions of the [SSCs]…can be performed.”[200] The monitoring system was also required to encompass the non-safety related equipment whose failure could prevent operation of safety-related functions. The licensee was to develop performance criteria for SSCs in terms of availability, reliability or operating condition and determine if the SSCs met the criteria. If performance was not achieved then the plant operator was required to monitor the SSC where it was “evaluated against…licensee-established goals.”[201] Goals were the same, practically, as

[198] U.S. Nuclear Regulatory Commission 1991, 31306.
[199] U.S. Nuclear Regulatory Commission 1991, 31308.
[200] U.S. Nuclear Regulatory Commission 1991, 31308.
[201] U.S. Nuclear Regulatory Commission 1991, 31308.

performance standards, but the term *goal* signified that the SSC had not met the standard. The SSC was therefore being monitored with actions taken to achieve the performance standard as a goal. The NRC also advised licensees that "the assumptions in and results of probabilistic risk assessments (PRAs)…should be considered when establishing goals."[202] The second implementation approach, detailed in paragraph (a)(2), was to systematically maintain SSCs that *were* meeting performance standards. This approach was the construction of the ultimate goal of the Maintenance Rule; implementation of effective programmatic preventive maintenance that kept a plant safely running as designed and operated. Additionally, paragraph (a)(3) required that the plant licensee implement preventive maintenance for the Maintenance Rule itself. The implementations of the (a)(1) and (a)(2) methods had to be maintained by the licensee with the NRC requiring that "adjustments are to be made to goals, monitoring, or preventive maintenance requirements."[203] Finally, the impact of maintenance activities themselves on overall plant operations were required to be assessed. The effects on plant safety functions, caused by taking SSCs out of service, had to be evaluated as part of maintenance planning, scheduling and execution. The act of performing maintenance had two goals: to maintain plant safety and, to not decrease plant safety.

The wording of the maintenance rule was sparse and occupied less than half a page in the Federal Register, but it framed several significant areas. First, the paired objectives of the maintenance rule explicitly coupled critical plant equipment to balance-

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[202] U.S. Nuclear Regulatory Commission 1991, 31308.
[203] U.S. Nuclear Regulatory Commission 1991, 31308.

of-plant (BOP) SSCs that had not been typically considered linked to the functioning of safety related SSCs. The Maintenance Rule was providing direction to construct the logical knowledge coupling to overlay the physical links between safety and non-safety related SSCs; links that were not traditionally legible to the licensees nor the regulator. This legible coupling was a result of lessons learned from the Three Mile Island (TMI) accident. It was the lack of recognition of system coupling that contributed to the failure of TMI-2's balance-of-plant condensate polisher that was to become the initiating accident event. Second, the NRC's call out, in describing the rule, to use PRA technology to identify the risks of accident sequences, was also tied to the TMI-2 experience. Furthermore, it was recognition and implementation of Rasmussen's WASH-1400 development of effective PRA. Third, and significantly, SSC monitoring was explicitly required to be "predictive in nature, providing early warning of degradation."[204] The monitoring program was to be sufficiently sophisticated to incorporate predictive maintenance. No longer could indication of failure be the failure itself. The U.S. commercial nuclear system was moving away from the fossil fuel mentality of run-to-failure and building the philosophy of run-with-maintenance. To start the run, the NRC established a five year implementation timeline with their own regulatory guide to be developed in the first two years, thus giving the industry three years to fully implement the maintenance rule by 10 July 1996

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[204] U.S. Nuclear Regulatory Commission 1991, 31308.

NUMARC-93-01 - Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants

The industry had not previously responded immediately to NRC prompts, in association with the proposed rule, to develop maintenance rule implementation standards. In March 1992, with the final rule published by the NRC nine months earlier, the Nuclear Management and Resources Council (NUMARC), presented a draft maintenance program guide for implementing the maintenance rule, *Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants, NUMARC 93-01, Revision 1*.[205] Upfront, in the first paragraph of the guide, NUMARC stated that the "industry agrees with [the] intent of the Maintenance Rule" where effective maintenance provides "reasonable assurance that key structures, systems, and components are capable of performing their intended functions."[206] The NRC and the nuclear industry Maintaining properly functioning equipment was inherent to safe, reliable, and cost effective plant operations.

The industry's guideline added fill to the Rule's minimal framing. It provided actionable guidance to the utilities for each required area of the Rule: 1) scoping, or how the utility would determine what SSCs fell under the purview of the Maintenance Rule, 2) constructing the risk and performance criteria for (a)(1) goal setting and monitoring, 3) developing the (a)(2) program of effective preventive maintenance to ensure scoped SSCs were continually functioning safely and reliably, 4) developing the (a)(3) required

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[205] Nuclear Management and Resource Council 1992.
[206] Nuclear Management and Resource Council 1992, 1.

methods to assess the effects of maintenance actions themselves on the safe and reliable functioning of the plant and, 5) self-assessment of the effectiveness of a utility's implementation of the Maintenance Rule. While framing in detail for these areas, the guidance was not absolutely prescriptive. Each utility was to "implement a plant-specific program to meet the intent of the Maintenance Rule."[207] NUMARC 93-01 straightforwardly stated "utilities may elect other suitable methods or approaches for implementation."[208]

The Rule was mandatory, but did not detail specific actions. The industry guidelines were not mandatory and provided suggestions to allow for "significant flexibility for individual utility implementation."[209] It was local construction of the Maintenance Rule beyond the higher administrative functions of the utility and down to the operational level at each individual plant. Furthermore, the industry guideline emphasized that its intent was to "maximize the use of existing…programs, studies, initiatives and data bases, and to minimize the necessity for new or expanded programs."[210] This allowed the utilities and individual plants to use their maintenance structures either as-is, if they met the Maintenance Rule requirements, or to adjust and reconfigure them. Conservation of plant resources and utilization of any existing effective maintenance programs was, as made clear by the nuclear industry at the 1988 workshop, critical to practical and cost effective implementation of the Maintenance Rule.

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[207] Nuclear Management and Resource Council 1992, 1.
[208] Nuclear Management and Resource Council 1992, 1.
[209] Nuclear Management and Resource Council 1992, 2.
[210] Nuclear Management and Resource Council 1992, 2.

Scoping

NUMARC 93-01's recommended guidance began with a description of the methodology to determine what SSCs were within scope of the Maintenance Rule. It took, verbatim, the Rule's stated characteristics of safety-related and non-safety related SSCs as checklist items for scope determination. There were three determining areas of functionality that safety-related SSCs were critical to ensure:

> - The integrity of the reactor coolant pressure boundary; [or]
> - The capability to shutdown the reactor and maintain it in a safe shutdown condition; and [or]
> - The capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposure comparable to 10 CFR Part 100 Guidelines?
>
> A <u>yes</u> answer to all [any] one of the above will identify that the SSCs are within the scope of the Maintenance Rule.[211]

Similarly, for nonsafety related SSCs scoping was determined by answering the following questions, with a "yes" to any of them indicating the SSC was scoped within the Maintenance Rule.

> Are the nonsafety-related SSCs relied upon to mitigate accidents or transients?[212]

SSC functions that could mitigate accidents or transients (abnormal conditions) were functions that did not *directly* affect the reactor pressure boundary or shutdown

[211] Nuclear Management and Resource Council 1992, 4.
[212] Nuclear Management and Resource Council 1992, 4.

capabilities etc., but were critical in responding to problems and maintaining overall plant safety and operations such as fire suppression systems.

> Are the nonsafety-related SSCs used in plant Emergency Operating Procedures (EOPs)?[213]

For SSCs used in EOPs, and to be scoped in the Maintenance rule, they had to be the "principal means identified in EOPs to control key plant safety parameters or mitigate the effects of core damage and radioactive release."[214] For example, if fire water systems were planned to be used as an emergency source of core coolant during an emergency they would fall under the Maintenance Rule if they were "normally aligned and interfacing" with the coolant system.[215] In other words, if the system required extensive reconfiguration and setup for emergency response it was not considered a principal response means for EOPs and was outside the scope of the Maintenance Rule.

> Will the failure of nonsafety-related SSCs prevent safety-related SSCs from fulfilling their safety-related function?[216]

Here, the plant operators would need to evaluate the interdependencies between plant SSCs to determine what nonsafety-related SSC failures would directly interfere with the functioning of safety-related SSCs. A typical example, that the guide presented of this type of system, was a power supply the provided power to solenoids used to open and

[213] Nuclear Management and Resource Council 1992, 5.
[214] Nuclear Management and Resource Council 1992, 5.
[215] Nuclear Management and Resource Council 1992, 5.
[216] Nuclear Management and Resource Council 1992, 6.

close valves of safety-related systems. To say the least, for a nuclear power plant, reliable coolant system valve operations were of critical importance.

> Will failure of the nonsafety-related SSCs [directly] cause a reactor SCRAM or actuation of safety-related systems?[217]

Finally, the Maintenance Rule and the guide asked what nonsafety-related SSCs would automatically shutdown the reactor (force it to SCRAM) or activate safety systems (whose activation would most likely force a SCRAM anyway). Examples of this situation would be turbine and generator trips (shutdowns) that would initiate a SCRAM and loss of offsite power that would cause safety-related emergency diesel generators to automatically spin-up.

Of interest is that NUMARC added the word "directly" to the SCRAM question and to its description of the Rule's question on fulfilling safety-related functions. NUMARC directly stated that this was to "bound the scope to a direct initiator and avoid lower level (cascading) effects."[218] Everything in the plant was not to be maintained by the Maintenance Rule, but everything in the plant was to have maintenance performed "dependent upon economic importance and on the consequence of SSC failure on power operation."[219] This constrained the resources spent upon Maintenance Rule implementation and allowed many SSC areas of a nuclear power plant to remain under the fossil fuel maintenance philosophy; run to failure or run to the limit of cost effectiveness. With that thought, I would perhaps call it, "fail to the limit of cost

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[217] Nuclear Management and Resource Council 1992, 7.
[218] Nuclear Management and Resource Council 1992, 6.
[219] Nuclear Management and Resource Council 1992, 8.

ineffectiveness," where the plant operator eventually realizes that constantly fixing a broken system does not make good business sense.

Risk and Performance Standards

As per the guide, with the plant SSCs scoped under the Maintenance Rule, the plant operators were now ready to enter the core of the Maintenance Rule; the (a)(1) requirement. The operator was required to construct "risk significance and performance criteria to determine which SSCs must have goals established and monitoring activities performed."[220] In other words, what was the acceptable level of risk of failure and what was the minimum performance required for any given SSC? With those standards known, and an SSC assessed against them, the goal of meeting those risk and performance criteria would be set if the SSC fell short of the standards. The plant operator would monitor the SSC performance until it improved and achieved the established goal, or standard.

To determine SSC risk significance the guide recommended leveraging established assessment methods (demonstrating the stated intent of utilizing existing systems of maintenance activities) such as: Individual Plant Examination (IPE) that assessed specific plant risk vulnerabilities to severe accidents, data from previously accomplished Failure Modes and Effects Analysis (FMEAs), results from Reliability Centered Maintenance assessments that identified safety-significant equipment,[221] and

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[220] Nuclear Management and Resource Council 1992, 10.
[221] Pacific Northwest Laboratory 1991.

Probability Risk Assessments (PRA). In addition to formal risk assessment methodologies, especially at plants where risk programs were lacking, the guide stated that "operations and systems engineers agreeing on the set of SSCs" would be an acceptable process and "review meetings of systems engineers for each system is appropriate."[222] Here we see an acceptance and encouragement of utilizing practical operating experience (OE) to facilitate risk determination.

Operating experience, in addition with existing methodologies, was also a primary method to establish SSC performance criteria. The guide positioned OE as a critical and practical method, sourced from across the industry, and used it in conjunction with "industry codes and standards, failure rates, duty cycles and performance-related data" to establish measures of availability and reliability for SSCs.[223] Furthermore, recognizing that nuclear power plants were not standardized across the industry in design, build, or operation (even those operated by the same utility company) NUMARC called out that performance criteria could and would often be plant-specific. Finally, NUMAR addressed those SSCs that were determined to be "intrinsically reliable" such as cabling, metal supports, and even the reactor vessel and containment.[224] These SSCs were viewed as being able to perform their function without preventive maintenance and therefore did not require (a)(1) classification with goal setting. I would characterize these SSCs as passive rather than active SSCs such as valves, switches and pumps; they had no moving parts. For those SSCs that did not meet risk and

[222] Nuclear Management and Resource Council 1992, 11.
[223] Nuclear Management and Resource Council 1992, 11.
[224] Nuclear Management and Resource Council 1992, 12.

performance criteria or were not determined to be passive and, hence, inherently reliable, the plant operator had to set goals and establish a system monitoring to track progress toward meeting those risk and performance goals.

Goals and Monitoring

For nuclear power plant operators, effectively navigating the Maintenance Rule's (a)(1) landscape requires knowledge of several things: where you are going, your progress being made in getting there, and what navigation tools are best to use. NUMARC's 93-01 guideline laid out these knowledge needs in describing goal setting and monitoring. Goal setting, established the performance level destination for the maintenance program trip. They were to be defined and planned by the plant operators in order to "proceed from the present performance status toward a level of improved performance…in a measurable way."[225] Successful navigation to improved performance was to be assessed at different levels from plant, through system and component, to structure.

The highest level was overall plant performance, evaluated in either safety or nonsafety terms, e.g. frequency of reactor scrams or general plant availability to generate electricity. Next, was at the system level; where the industry expected to establish the majority of goals. Systems were the fundamental operational elements of a nuclear power plant. Here, the focus was on systems reliability and availability to

[225] Nuclear Management and Resource Council 1992, 12.

perform their safety functions. The guide also emphasized that “due to plant-specific redundancy and diversity, an SSC failure does not necessarily cause a loss of safety system function.”[226] NUMARC was essentially reminding plant operators that having redundant systems could mean that goal setting at the system level, and at the lower system component level, could conceivably be less stringent and therefore easier and more cost effective to reach and maintain. The systems (and their components) of a redundant system did not, individually, have to be as reliable as a single system. This thinking fit into the overall concept of selling the Maintenance Rule to the utilities where existing resources, methods and equipment itself could be utilized with little to no modification for more cost effective Rule compliance. Finally, NUMARC presented the structure level as typically not being part of the (a)(1) environment, due to its passive nature, and therefore not requiring goal setting. Even with that thinking, NUMARC did not completely eliminate structure from possible (a)(1) goal setting. It suggested goals on “limits for cracking, corrosion, erosion…or some other such type criteria.”[227] Again, structure had the potential for not incurring a high maintenance rule cost. On an (a)(1) plan, with the destination goals identified, the plant operators now had to track the direction and progress to their set goals.

[226] Nuclear Management and Resource Council 1992, 13-14.
[227] Nuclear Management and Resource Council 1992, 14.

Monitoring

The guideline took monitoring through each of the SSC levels with the overall guidance that, “Monitoring should consist of periodically gathering, trending, and evaluating information pertinent to the performance, condition, and availability of the SSCs and comparing the results with the established goals to verify that the goals are being met.”[228] The described monitoring was much like dead-reckoning navigation often used by aviators. It used the taking of “fixes” to locate in route positions to ensure the maintenance program was effectively on the correct course to the destination goal. As the fixes were plotted they were to assist the operators in “recognizing improving performance trends” thus providing legible monitoring indications.[229] The 93-01 guideline emphasized that performance monitoring not only had to be administratively legible, but for SSCs whose failure could cause the loss of a safety function it had to “be predictive in order to provide timely warning.”[230] As with aviation navigation the maintenance program had to stay ahead of situations where a mountain (or loss-of-coolant-accident) could suddenly appear out of the clouds with no time to avoid it.

Ultimately, if SSCs did degrade in function or fail, the guideline stated that system of maintenance monitoring “should provide a means for determining the effectiveness of previous corrective actions.”[231] Any executed course corrections had to be evaluated to include assessing that the actions themselves did not inadvertently cause deviation

[228] Nuclear Management and Resource Council 1992, 12.
[229] Nuclear Management and Resource Council 1992, 14.
[230] Nuclear Management and Resource Council 1992, 14.
[231] Nuclear Management and Resource Council 1992, 14.

from progress toward the performance goals. The monitoring activities were also to take into account use of limited plant resources and were to, as much as possible, use any existing applicable monitoring processes and programs to meet 50.65 requirements. NUMARC also emphasized that "practical monitoring...should not require extensive analytical modeling or excessive data collection."[232] The plant operators were not to develop a unique Maintenance Rule monitoring system if at all possible. To further simplify implementation, the guideline provided specific examples of performance parameters to monitor at most levels of the plant. At the system level monitoring was to simply focus on "availability and/or reliability" of the particular system.[233] For the component level, the guideline suggested monitoring of data such as "flow, pressure...temperatures, [and] vibrations."[234] Methods for this component monitoring could be accomplished using non-destructive analysis of "oil, grease...infrared…acoustics, and electric continuity."[235] Similarly, for the structure level the guideline called for "non-destructive examination, visual inspection, vibration monitoring...thickness monitoring, [and] corrosion monitoring" of structures such as the reactor containment and foundations for major components such as pumps and turbines.[236] These approaches and methods were well within the realm of existing plant maintenance and surveillance activities. In contrast, at the plant level individual SSCs goals are not monitored. Monitoring focuses on the working integration of all of the plant SSCs performing as a comprehensive whole. In other words, these SSCs, in the

[232] Nuclear Management and Resource Council 1992, 14.
[233] Nuclear Management and Resource Council 1992, 15.
[234] Nuclear Management and Resource Council 1992, 15.
[235] Nuclear Management and Resource Council 1992, 15.
[236] Nuclear Management and Resource Council 1992, 16.

context of a functioning power plant, have met their performance goals and are operating as a plant system; therefore, they are "[demonstrating] the effectiveness of the preventive maintenance program established under (a)(2)."[237] This fully operational destination is the ultimate (if not theoretical) goal of the Maintenance Rule.

Goal Evaluation

With being in the (a)(2) Maintenance Rule condition as the objective for SSCs the guideline presented two aspects of (a)(1) goal evaluation: 1) whether or not a goal was still effective and, 2) if the SSC had reached its performance goal and could therefore move from (a)(1) condition to (a)(2). First, evaluating a goal was meant to determine if it was still a valid measurement of performance since it had initially been put into place. Had something changed with an SSC or with the functioning of the maintenance program that would require a change to the SSC's performance goal?[238] The 93-01 guideline provided examples of factors that could invoke a change such as "increased availability/reliability, improved preventive maintenance, change in design…[or the] original goal determined unrealistic."[239] I would characterize this goal evaluation as goal setting (perhaps resetting) and monitoring of goals. Second, the aspect of goal evaluation in determining if an SSC had achieved its intended performance goal was further defined to where "it must have shown performance improvement over one monitoring cycle or, having reached its established goal, maintained performance at or

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[237] Nuclear Management and Resource Council 1992, 15.
[238] Nuclear Management and Resource Council 1992.
[239] Nuclear Management and Resource Council 1992, 17.

above that goal for a period of one monitoring cycle."[240] The goal was not simply a point of performance, but was the establishment of consistent, safe, and reliable working operations; operations to be prevented from future failure under the surveillance and maintenance activities of (a)(2).

Preventive Maintenance

Operating in (a)(1) is not a location a plant operator wishes to inhabit. It is an area of regulatory and industry get-well scrutiny since it is perceived to indicate sub-standard performance. If monitoring demonstrates that SSC performance goals have been achieved then the SSC can relocate to (a)(2) and be maintained with the actions of a preventive maintenance program. This is where the Maintenance Rule primarily operates and where most maintenance is planned and executed. The work of maintenance has only started after moving from (a)(1) to (a)(2). In (a)(2) is where we see the implementation of continuously active and effective maintenance versus the event driven maintenance that characterized the historically traditional run-to-failure philosophy. In the 93-01 guideline, NUMARC described several fundamental activities that form (a)(2)'s preventive maintenance structural backbone: periodic maintenance, predictive maintenance, failure trending, and identification of maintenance preventable failures. Periodic maintenance was the most straightforward in concept and the guideline called it "routine" and gave examples such as "inspections...testing...overhauls...component replacement...lubrication...and filter

[240] Nuclear Management and Resource Council 1992, 16.

changes."[241] It sounded much like automobile maintenance. In contrast, predictive maintenance used advanced techniques to enhance ability to know the condition of the inner workings of SSCs even while they are operating. This included “vibration analysis... bearing temperature monitoring, lube oil analysis...and motor voltage and current checks.”[242] These checks were intended to make legible trends in off-normal conditions that could indicate (or predict, with enough data points, operating experience, and analysis) potential SSC failures before they occurred. The condition of a power plant, and its probable risk of failure, could be assessed much like inferring the condition or health of the body with a blood test and an electrocardiogram. Furthermore, NUMARC’s emphasis on these minimally intrusive inspections, accomplished without taking equipment out of service, were methods that could further allay industry’s concerns of the cost of implementing the Maintenance Rule. Trending of failures was also to be used when SSCs did fail by analyzing local plant historical data and operating experience from across the industry. This was to provide feedback analysis for “making adjustments to the preventive maintenance program” and it would also function to distribute common programmatic maintenance activities and information throughout the industry.[243] Finally, the guideline required that preventive maintenance be evaluated to determine if the maintenance itself could potentially be causing SSC failures. This was termed “Maintenance Preventable [Functional] Failures.”[244] MPFFs were primarily used to characterize and capture failures caused by mistakes made during the execution of

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[241] Nuclear Management and Resource Council 1992, 18.
[242] Nuclear Management and Resource Council 1992, 19.
[243] Nuclear Management and Resource Council 1992, 19.
[244] Nuclear Management and Resource Council 1992, 19.

maintenance; which were described as the "incorrect implementation of correct maintenance procedures."[245] Interestingly, MPFFs also captured "the implementation of incorrect maintenance procedures."[246] Here was an integrated self-assessment feature that provided corrective feedback on how well maintenance tasks were engineered. Task construction was decoupled from task execution, which could also make failure scenarios more legible for root-cause analysis. Finally, MPFFs may identify failures that could be attributed to not performing maintenance needs communicated in industry reports and equipment problems caused by simply failing to perform "maintenance activities that are normal and appropriate to the equipment function and importance."[247] Having the MPFF construct in place appears to be a way to contribute to sharing of SSC specific maintenance information and operating experience across the industry. Seemingly ironically, correctly performing maintenance can also increase the risk of failure.

Removing Systems from Service

The impacts of performing plant maintenance are typically considered to be increases in safety and reliability. With planned, preventive maintenance SSCs are out of service less often due to failure and are capable of performing their safety functions. However, performing that failure-preventing maintenance causes, practically, equipment functional failures; the equipment is functionally out of service for the duration of the

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245 Nuclear Management and Resource Council 1992, 20.
246 Nuclear Management and Resource Council 1992, 20.
247 Nuclear Management and Resource Council 1992, 20.

maintenance. With (a)(3), the Maintenance Rule recognized the potential negative consequences of planned maintenance or what I would describe as *commanded* service failures. The Maintenance Rule required that utilities evaluate the impact of these commanded failures on overall plant safety as they planned and implemented maintenance activities. The 93-01 guideline provided an extremely high-level methodology for "assessing the cumulative impact…on safety functions upon removal of SSCs from service during power operations."[248] It simply required that the utility identify key plant safety functions and the SSCs required to maintain those functions and consider the effects of maintenance outages. For example, should a backup diesel generator be taken down for maintenance during severe weather (to include solar storm activity) when there is an increased probability that offsite power could be lost and the likelihood of its need is more probable?[249] Maintenance fixes things but, as Lee Vinsel pointed out, it can also break things.

Evaluating Maintenance Effectiveness

With (a)(3) also requiring utilities to formally evaluate their maintenance programs for Maintenance Rule compliance "at least annually [periodically, at least on a refueling cycle basis," the 93-01 guideline described how the utility should approach the self-assessment.[250] First, were SSC goals being achieved and were they still applicable to

[248] Nuclear Management and Resource Council 1992, 22.
[249] Interviewee 004 14 June 2018.
[250] Nuclear Management and Resource Council 1992, 23.

their original purpose? If the goal had been reached and the SSC had met its performance criteria "over a period of at least one monitoring cycle" the SSC could then be moved from (a)(1) monitoring to (a)(2) preventive; the all-encompassing goal for all SSCs.[251] If the goal was not being met the utility was to determine the root cause and take corrective action. The root cause analysis could also include a review of MPFFs to assess if (a)(1) maintenance itself was a contributor to not meeting goal criteria. The guideline further emphasized that during the annual self-inspection the utility should also review industry operating experience to gain actionable insight on probable failures of similar SSCs across the commercial nuclear enterprise. Second, the annual review also was to allow the utilities to systematically assess how their maintenance program was effectively balancing SSC unavailability and reliability as previously discussed for removing systems from service. The guideline described the review as: "Assessing how much maintenance is enough involves balancing the time that an SSC is out of service due to maintenance, and the likelihood that maintenance errors will cause scrams or trips."[252] I would describe this as the balance between commanded service failures (maintenance) and uncommanded service failures (unreliability).

[251] Nuclear Management and Resource Council 1992, 23.
[252] Nuclear Management and Resource Council 1992, 24.

DRAFT Regulatory Guide DG-1020 - 30 November 1992

In late 1992 the NRC issued, for public comment, "Draft Regulatory Guide DG-1020, Monitoring the Effectiveness of Maintenance of Nuclear Power Plants."[253] In the give-and-take development progression of regulatory guides and industry guidelines, DG-1020 was the NRC's first engagement with NUMARC's 1992 93-01 guidance of how the industry planned to implement the Maintenance Rule. The 93-01 draft had been industry's first response to the NRC's initial 1989 draft guide DG-1001 and the published 1991 final rule 50.65. Now, with the 1992 NUMARC guideline formally presented by industry, the NRC had acquired the industry target to aim their regulatory guide toward for eventual endorsement. The initial NRC guide had been quite detailed since it could have conceivably been the only implementation guide if the industry had not developed its own standards. It also had pointedly described to industry what the NRC was generally expecting to see in acceptable implementation methods. NUMARC had closely followed much of the initial NRC guide to build their 93-01 guideline. In fact, the NRC staff had worked directly with NUMARC "to ensure that the requirements and intent of the maintenance rule would be addressed."[254] This approach was both logical and practical since directly implementing the Maintenance Rule as per the NRC's statements required little interpretation and could be more rapidly executed with more than reasonable expectations of approval by the regulator.

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[253] U.S. Nuclear Regulatory Commission 1992a, 55286.
[254] U.S. Nuclear Regulatory Commission 1992a, A-6.

With the most recent 1992 NUMARC 93-01 guideline providing a robust industry way-forward, the NRC pared back presentation of the explicit detail in DG-1020. As in DG-1001, DG-1020 provided explanatory descriptions of each area of 50.65 and discussed monitoring of safety and non-safety-related functionality of systems, structures and components. The previously included maintenance theory, techniques, and practices were not discussed in the less than five pages of text. The intent of the content remained consistent with the early draft guide, but its detail had been effectively transferred to the industry guideline. Like the maintenance rule that broadly defined the requirements of effective maintenance the regulatory guide now only had to broadly describe the implementation methods that would meet the requirements. As the NRC had emphasized from the beginnings of the maintenance rule discussion, the implementation standards were to be primarily constructed by industry since the rule was to be "performance based and results-oriented."[255] DG-1020 was the last NRC draft proposal issued prior to publication of the final regulatory guide. In the draft, the NRC came forward, sans reservation, with its acceptance of the industry's approach to implementing the Maintenance Rule; "the proposed regulatory guide endorses the NUMARC guidance without modification."[256] As originally planned, the first two years of implementation of the Maintenance Rule saw the construction and pairing of the NRC's regulatory guide and NUMARC's (industry's) guideline. In conjunction with the Maintenance Rule, these methodological tools formed the foundation of the nuclear power plant regulatory maintenance environment.

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[255] U.S. Nuclear Regulatory Commission 1992a, A-5.
[256] U.S. Nuclear Regulatory Commission 1992a, A-6.

NRC Regulatory Guide 1.160

The NRC published the base version of Regulatory Guide 1.160, *Monitoring the Effectiveness of Maintenance at Nuclear Power Plants*, in June 1993.[257] Other than omitting the administrative appendixes of DG-1020, RG 1.160 was much the same as its draft predecessor. The one significant change was the carrying forward, from DG-1020, a comment on regulatory requirements concerning reliability performance criteria of emergency diesel generators. In DG-1020 the brief comment was related to the station blackout rule (10 CFR 50.63)[258] and issues regarding emergency generators that could overlap with the maintenance rule (10 CFR 50.65).[259] The comment was expanded in 1.160 to a full discussion of how the requirements of 50.63 could be met under the execution of 50.65. Generator reliability values "could be used as a goal or as a performance criterion for emergency diesel generator reliability under the maintenance rule."[260] Ultimately, "plant-specific emergency diesel generator reliability and unavailability should be monitored as goals under 10 CFR 50.65(a)(1) or established as performance criteria under the plant's preventive maintenance program under 10 CFR 50.65(a)(2)."[261] Here was evidence that the NRC remained aware of industry's continued concern over regulatory burden and the resources required to meet the requirements of yet another rule. With aspects of these two rules closely aligned, the NRC explained in detail how a plant could meet station blackout coping strategies

[257] U.S. Nuclear Regulatory Commission 1993.
[258] U.S. Nuclear Regulatory Commission 1988a.
[259] U.S. Nuclear Regulatory Commission 1991.
[260] U.S. Nuclear Regulatory Commission 1993, 1.160-3.
[261] U.S. Nuclear Regulatory Commission 1993, 1.160-3.

with diesel generators while simultaneously ensuring the effectiveness of maintenance on those generators. Here was presented not only a method to implement effective system maintenance, but also a resource conserving strategy to integrate the execution of multiple regulatory rules.

Finally, RG 1.160 formally endorsed the May 1993 version of NUMARC 93-01, Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants, as the final production guideline that "provides methods acceptable to the NRC staff for complying with the provisions of 10 CFR 50.65."[262] The May 1993 version of NUMARC 93-01 was finalized as the result of a question presented by the NRC when it issued DG-1020 for public comment. The NRC queried if the 93-01 guidance's use of PRA methods to identify SSC risk significance would "satisfactorily address low-frequency, high-consequence contributors."[263] In other words, could PRA, as simply described in the draft of 93-01, potentially miss aspects of SSC risk significance? NUMARC assessed and responded to this question during a verification and validation (V&V) process "with NRC staff observation, to test the guidance document on several representative systems."[264] As a result of the V&V, the risk significance section of 93-01 was revised by NUMARC. It now explicitly described (as noted by the NRC staff itself in its response to NUMARC's reply to the question) “establishing lists of risk-significant systems by three different PRA-based methods and then having an expert panel review the results.”[265] These were distinct methods to calculate risk significance

[262] U.S. Nuclear Regulatory Commission 1993, 1.60-4.
[263] U.S. Nuclear Regulatory Commission 1992b, 55287.
[264] U.S. Nuclear Regulatory Commission 1993, 1.160-3.
[265] Nuclear Management and Resource Council 1993, 10.

and included: 1) “Risk Reduction Worth,” 2) “Core Damage Frequency Contribution” and, 3) “Risk Achievement Worth.”[266] With this final adjustment to the industry’s approach of making legible risk significance, 93-01 was ready for integration as a component of commercial nuclear power plants.

Lessons Learned from Early Implementation of Maintenance Rule at Nine Nuclear Power Plants (NUREG-1526) - August 1995

The first phase of the Maintenance Rule implementation constructed the 93-01 industry guideline and the 1.160 NRC regulatory guide; the methodological technologies of implementation. The subsequent phase of implementation put these technologies into effect at operating plants and assessed their effectiveness. The NEI and NRC coordinated to select nine sites, for evaluation, that had volunteered to be early implementers of the Maintenance Rule. The sites had worked to implement the Maintenance Rule using 93-01 and 1.160 as guiding frameworks. The site selections included several utility companies and encompassed plants from the NRC’s four regulatory regions: Maine Yankee and Pilgrim (Region I), Crystal River, Hatch, Shearon Harris and Vogtle (Region II), Byron (Region III), and Grand Gulf and South Texas (Region IV).[267] The selection of nine plant sites included five plants operating PWRs and four operating BWRs and therefore provided maintenance visibility of both reactor designs used by the U.S. utilities. Starting in September 1994 and ending in March of 1995 the NRC visited the nine sites. Their objective was to “determine the strengths and

[266] Nuclear Management and Resource Council 1993, 19-20.
[267] U.S. Nuclear Regulatory Commission 1995.

weaknesses of the implementation of the rule at each site…[so]…other licensees [could] consider this information when developing programs for implementing the rule."[268] The inspection domain was diverse with its inclusion of the major types of technologies, multiple operating companies, and all of the NRC regions. It is also noteworthy that the NRC was actively working with industry in providing constructive feedback to plant licensees and to their own inspectors; the regulator's efforts were weighted toward maintenance system effectiveness success rather than merely citing compliance deviations. The NRC examined how effectively the licensees were meeting the intent and the requirements of each of the Maintenance Rule sections and how they interpreted and used the industry and NRC guides even as they were non-mandatory.

Scoping

The NRC observed that a licensee was not scoping in various non-safety related SSCs because they had a history of high reliability. According to the licensee the SSCs rarely failed so they did not consider them to be a required subject of the Maintenance Rule. This was their reasoning even though if the SSC failed it "could prevent safety-related [SSCs] from fulfilling their safety-related functions."[269] The licensee was, in probable functionality, giving these SSCs a reliability of one instead of zero (for failure), thereby effectively making the assumption that they had *not* failed in any PRA model used to assess safety significance. This thinking functionally removed the SSC from

[268] U.S. Nuclear Regulatory Commission 1995, 1.
[269] U.S. Nuclear Regulatory Commission 1991, 31324.

failure chain of events and, of course, would have removed it from the view of a formal maintenance program initiated and shaped by the Maintenance Rule. The NRC called out paragraph (b)(2)(iii) that stated, referring non-safety related SSCs, “”whose failure *could* cause a reactor scram or actuation of safety related system” [emphasis added]”” and said that the licensee had misinterpreted it by not assuming the potential for actual failure as described.[270] In similar thinking, the licensee had not included a water circulating system since it was comprised of four separate redundant systems or trains. Again, the thinking was, if only one train failed the plant could still safely operate. The NRC disagreed and stated that the “licensee’s approach…is not conservative enough and does not meet the intent of paragraph (b)(2)(iii).”[271] Furthermore, the licensee also argued that if the system failed (in this case the circulating water system) a technician would take action to keep the reactor from scraming. In the operators’ thinking, running to SSC failure was normally acceptable if there was another SSC available to take over functions or there was someone to intervene after failure to keep the plant running.

In the NRC’s assessments there were other times where the disagreement was not as clearly defined and did not directly involve the Maintenance Rule. NUMARC 93-01 stated that the potential scoping of hypothetical failures such as those “that could result from system interdependencies but have not been previously experienced is not required.”[272] The licensee interpreted this as if the SSC had not failed in the past then it was classified as a hypothetical failure and did not have to be scoped. The NRC

[270] U.S. Nuclear Regulatory Commission 1995, 8.
[271] U.S. Nuclear Regulatory Commission 1995, 9.
[272] Nuclear Management and Resource Council 1993, 11.

believed "that the *hypothetical failures* described in NUMARC 93-01 refer to two or more events (not previously experienced or analyzed) that occur simultaneously and result in a reactor scram or safety actuation."[273] The NRC disagreed with the licensee's view, but left space to justify the licensee's view by describing its own view as an interpretation also. They then recommended that NUMARC clarify their hypothetical statement in an update to 93-01. In another situation the licensee argued the NUMARC guide had applied vague language when it used the words "significant fraction" in the definition of what level an SSC provides functional capabilities to mitigate core damage or radioactive release. The licensee added additional language that clarified how they would evaluate SSCs and the NRC agreed with their approach.

Risk Determination

The plants primarily used PRA augmented with expert panels to determine the level of risk or safety confidence they had in their SSCs. Supplemental RRW, RAW, and CDF tools were used by various licensees, in various combinations, as was promoted in the production version of 93-01. The NRC noted, of these additional tools, that "none was indispensable as long as the results were reviewed and evaluated by a qualified expert panel."[274] In the NRC's assessment, it was the panel of experts that had the most effective impact on risk determination by examining PRA assumptions. They found a high level of expertise and experience in the members of the panels and

[273] Nuclear Management and Resource Council 1993, 11.
[274] U.S. Nuclear Regulatory Commission 1995, 13.

in their understanding and effective use of PRA. They commented that those sites who used expert panels in PRA risk determinations and also in evaluating when SSCs should move from (a)(1) to (a)(2) and other areas of the maintenance rule were also those who had established permanently standing panels. Their objective was "to maintain a *living* PRA" with regular updates [emphasis in orginal].[275] In considerable contrast, three of the nine sites had only temporarily created expert panels to perform PRA analysis for implementation of the Maintenance Rule. Most significantly, they did not plan to perform regular updates to the PRA other than when major changes were made to the plant; which would also require reconstituting the expert panels. With these findings the NRC recommended that the sites include an expert panel as a permanent part of their organization and consider using it in all functional aspects of the Maintenance Rule. They also recommended that the plants continually keep the PRA updated, i.e. alive and active within the organization.

Thinking Goal Setting vs. Preventive Maintenance

While the NRC found only one instance where a site classified an SSC under (a)(2), when it should have been an (a)(1), the licensees classified very few SSCs under paragraph (a)(1), with an average of three for all sites. In comparison, they placed an average of ` approximately 94 under (a)(2). The NRC was not critical of this extreme difference and considered it reasonable, but they did hint that starting from the opposite direction by first classifying SSCs under (a)(1), and monitoring, "would also meet the

[275] U.S. Nuclear Regulatory Commission 1995, 13.

intent of the rule."[276] It was clear that the NRC under understood the licensees' reasoning in their liberal and confident approach of assessing 97 percent of their SSCs as being effectively maintained by preventive maintenance; they instinctively wished to avoid being evaluated as having a poor maintenance program. That was a reasonable thought for a plant staff to hold being under the watch of the regulator and their own management. Demonstrate that things were going well and show that any deviations were the rare exception. Since the NRC wished to employ a more conservative approach to implementation of the Maintenance Rule they emphasized to the plant staff (and the staff's management) that having SSCs under (a)(1) was not an indication of poor maintenance. In fact, they lightly warned the licensees that it was better to take the more conservative approach and erroneously classifying an SSC under (a)(1) rather than under (a)(2) since that would be a rule violation.[277]

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Corrective Action

With an established history of repair experience, the NRC found the plants' in-place corrective action functions to be quite effective in meeting the (a)(1) requirements. They also saw evidence that the rule's new emphasis on maintenance was moving the plants to reassess and improve their root-cause analysis processes; they were getting better. Some of the plants had also assigned their expert panels to develop corrective actions which further improved maintenance effectiveness. Overall, the corrective

[276] U.S. Nuclear Regulatory Commission 1995, 18.
[277] U.S. Nuclear Regulatory Commission 1995.

maintenance at all of the nine plants was more than adequate to comply with the Maintenance Rule and the NRC did not have recommended improvements.

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Operating Experience

The Maintenance Rule was prescriptive in requiring that the nuclear industry make use of *industry* operating experience (OE) when establishing goals under (a)(1). It was not sufficient to learn from *your own* plant's maintenance activities; what *locally* failed and what did not, what *your* maintenance teams did right and what they did wrong. Under the Maintenance Rule it was to be learning from *all* of industry with sharing of information on the performance of SSCs and the maintenance required to achieve and maintain their safety and reliability; a shared system of common operating experience. The NRC team assessed that the licensees had, for the most part, considered OE when establishing goals. What they primarily found was an informal system that relied on sharing of "anecdotal data."[278] A collection of managed reliability and availability data either did not exist or it was generally difficult to access and to retrieve processed information. The NRC pointed out that at one site engineers did have ready access to data at individual computer terminals, but at the time, (the mid 1990s), it was not unusual for data queries to require formal requests to database managers which made it less likely for those developing goals to engage with this administrative burden. Ultimately, computer access was not the most significant constraint, it was the extremely limited existence of pooled data from other plants. The

[278] U.S. Nuclear Regulatory Commission 1995, 21.

industry did not have a process to effectively collect and share actionable data among its plant operators. Interestingly, the NRC itself assessed their own delayed realization "that licensees had not established a systematic and consistent method of collecting and using SSC reliability and availability data from other licensees when setting goals."[279] They candidly commented that this occurred to them only during their own post inspection discussions; an excellent example of the benefits of shared operating experience.

Monitoring and Trending (Predictive Maintenance)

The initiating events for corrective maintenance actions are fairly attention getting; something breaks and it stops working. Generally, it can be easy to literally see; a leak, a fracture, or corrosion and wear. If it's not readily visible it's evident from instrumentation; a voltage drop, a decrease in coolant flow, or (in a nuclear power plant) a change in radiation levels. This break-see-fix process was what the nuclear industry was accustomed to. It was a lagging activity. Eyeballs and gauges saw or registered what *had* happened, but they were not constructed to predict what *could* happen. The Maintenance Rule aimed to reconfigure, with a regulatory tool, nuclear power plant maintenance into (if not a leading activity), what nuclear engineer David Lochbaum describes as a "least lagging indicator."[280] The Maintenance Rule's mandated predictive maintenance would instantiate that indicator and allow the plant engineers, as

[279] U.S. Nuclear Regulatory Commission 1995, 21.
[280] Personal conversation at NRC Regulatory Information Conference (RIC) on 13 March 2018.

I would describe it, to see what's happening before it gets bad. With predictive maintenance, the monitoring of SSCs and the trending over time of any functional anomalies would move maintenance from break-see-fix to; approach-break, see, prevent-break, or as close to that as possible. During their initial look at the nine sites the NRC found that most of the plants were still lagging considerably.

The plants were, for the most part, still employing maintenance methods that kept them from seeing what was happening with an SSC while it was on its path to potential failure. Visibility would, without warning, suddenly occur with failure. The NRC specifically detailed their concerns with two poor visibility areas: the "monitoring of redundant trains", and where sites were attempting to execute the "trending of zero failures."[281] Trains are series of components that make up a system such as a fuel oil system or a compressed air system. Each would have pumps, valves and compressors that comprise the train that provide the system's operational functionality. For increased availability a system could have a redundant train with it sitting idle in standby mode awaiting either an automatic or manual initiating event to begin operation. It was with standby mode that the NRC, and in fact the industry, argued that visibility was lost. The sites were monitoring these multi-train systems (typical with the fuel oil and air systems) at the system level. They were assessing performance of the entire system and had "not established individual performance criteria and monitoring for each…train under the rule."[282] The concern was that while the operational train was being actively assessed (and showing that the *system* was meeting performance criteria) the non-operational

[281] U.S. Nuclear Regulatory Commission 1995, 23-24.
[282] U.S. Nuclear Regulatory Commission 1995, 23.

redundant train could have undetected, potential failure inducing degradation. NUMARC 93-01 was explicit in calling for the need to monitor standby trains: "The performance criteria for this type of system should include both the operational and standby (not operating) performance characteristics as applicable."[283] The NRC approved this overall industry recommendation with its endorsement of 93-01 and also reemphasized it to the operational plants in its lessons learned assessment: "The high reliability of one pump could mask the unreliability of the redundant pump."[284] The publication and sharing of the lessons learned were also making plant conditions more visible across the industry.

Conclusion

After completing this first look at the initial nine sites the NRC concluded that compliance with the Maintenance Rule *could* be practically implemented using the industry's NUMARC 93-01 guideline, but they qualified their assessment with: "if the recommendations in this report are taken into consideration."[285] They did not unequivocally say that the licensees were currently meeting 10 CFR 50.65 requirements; adjustments were needed for effective implementation. Adjustments were not primarily needed for the technical methodology of implementation (the NUMARC 93-01 guideline), but to aspects of plant engineers' fundamental thinking about implementation of maintenance programs, to include their regulation.

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[283] Nuclear Management and Resource Council 1993, B-4.
[284] U.S. Nuclear Regulatory Commission 1995, 23.
[285] U.S. Nuclear Regulatory Commission 1995, 33.

First, by not scoping, into the Maintenance Rule, redundant SSCs or those SSCs where it was felt that human intervention would prevent safety failures, the plant engineers were effectively privileging system failure over system safety and reliability. In opposition, the Maintenance Rule was moving to force formal maintenance program thinking into how the engineers viewed and responded to the *non-functioning* of a system; instead of failure acceptance, failure *prevention* was to be the baseline and critical maintenance mindset. Second, licensees' superficial approach to risk determination, utilizing non-permanent expert panels showed a scant recognition of effective organizational management. Also, their first-time and one-time PRAs demonstrated the licensees' view of regulatory compliance as more of an administrative box-checking exercise rather than actual actions. Third, the design of the Maintenance rule required, under (a)(1), plants to self-identify SSCs that were not meeting performance criteria. This rule classification and reporting made legible the licensees' reluctance to make problems known to either the regulator or their own management. This organizational constraint could also be seen as a constraint upon the construction of industry OE. The industry did not have a process or custom to share information or an inclination to create it in the first place. Fourth, where the industry did have established processes was with corrective maintenance. It was not surprising that corrective action activities were fairly robust since corrective action had always been the mainstay of maintenance with the Industry's run to maintenance philosophy. Finally, the industry needed to thoroughly develop its methods to construct and to continuously maintain its understanding of the condition or health of its plants. An instantiated technical environment of and, most critically, a philosophy of predictive maintenance was what the industry required to shorten or eliminate its lag of understanding system conditions prior to system failures. At this very early stage of implementation (prior even to the mandated implementation date of 10 July 1996) the licensees and the NRC inspectors were still getting a feel for the rule and their own guiding methodological tools. They were still establishing their footing with real-world implementation in operating plants with people historically accustomed to run-to-maintenance thinking rather than working in a run-with-maintenance system.   There were certainly lessons to be learned and looped back and defused throughout the commercial and regulatory nuclear power environment over the next year when the Maintenance Rule would become the law of the land inside the fences of nuclear plants across the United States. The lessons were documented; were the lessons learned?

Baseline Inspections - NUREG-1648 Lessons Learned Baseline Inspections NRC – October 1999

With the original nine pilot implementations and assessments the industry and the NRC had, as the aviation community might say, “Test flown the experimental version of the Maintenance Rule.”   They had proven the Rule could fly, but there were still design problems to be worked through.   The industry guideline, the regulatory guide, and the Maintenance Rule itself, had been put through their paces and were seen to be ultimately functional and workable; that is, ultimately operational if these three major system components were adjusted. The NRC explicitly described this adjustment process: "The need for revisions to the guidance documents (iterative process) arises from the general requirements of the rule versus specific guidance in the guidance documents and the flexibility given licensees to implement the requirements of the MR."[286] Since the Maintenance Rule was not prescriptive it would take time and back-and-forth interactions, for industry to develop and deploy Maintenance Rule implementation processes and methods, and for the NRC to understand and accept what the industry was doing and how to evaluate their performance. The NRC's first step toward evaluating the now flying Maintenance Rule began immediately after its official implementation.

Less than a week after the Maintenance Rule went into legal effect on 10 July 1996, the NRC began a tour of inspection of 68 nuclear power plant sites across the United States to perform a "maintenance rule baseline inspection (MBRI)."[287] Their objective was to verify that the licensees had implemented and were effectively executing maintenance programs meeting the requirements of 10 CFR 50.65 at each site. Now, with the Rule officially delivered to its users, came what the defense community might call Operational Test and Evaluation (OT&E).

NUMARC 93-01 Rev 2 Guideline

The nuclear industry engaged with what they learned from the pilot testing and NRC's assessments and revised NUMARC 93-01 with Revision 2 (April 1996)[288] before

[286] U.S. Nuclear Regulatory Commission 1999, 2-8.
[287] U.S. Nuclear Regulatory Commission 1999, vii.
[288] Nuclear Energy Institute 1996.

the final effective date of the Rule (10 July 1996). The NEI incorporated several changes. First, due to the lack of priority, or even recognition, that plant structures should be scoped under the Maintenance Rule the NEI added language for the monitoring of structures in a new section, "10.2.3 Monitoring the Condition of Structures."[289] The section called out the need for the predictive monitoring of structures such as reactor buildings and cooling towers "to provide early warning of degradation."[290] To further emphasize that structures should not be considered inherently reliable and do have a risk of failure, the language stated directly, "Monitoring of structures should be given the same priority as mechanical and electrical systems and components."[291] Merely because a plant component appeared to be (literally) rock solid it could not be ignored. Second, there was much clearer emphasis on using a site's monitoring programs if they previously existed before implementation of the Maintenance Rule. The original guideline contained a single sentence on the subject. Revision 2 expanded by stating that the information from existing programs could provide the technical basis that showed SSC performance was being effectively maintained through preventive maintenance. Here, the guideline was revised to remain consistent with industry's intent to always utilize existing resources, where possible, to meet Rule requirements. Also addressing effective use of resources, but not a direct result of the pilot testing, was that Revision 2 of 93-01 aligned itself with the amended (23 June 1993) Maintenance Rule. This change to the rule moved performance

[289] Nuclear Energy Institute 1996, 38.
[290] Nuclear Energy Institute 1996, 39.
[291] Nuclear Energy Institute 1996, 39.

evaluations from an annual requirement to one that was not to exceed 24 months. This cycle interval better aligned with integrating the evaluation with refueling maintenance outages depending on the needs and processes of specific sites.

The third significant change, informed by the pilot, was added emphasis put on accurately documenting the functions of Maintenance Rule SSCs to ensure the utility fully understand loss of plant function if they were taken out of service for maintenance. This was a direct action to ensure effective risk evaluation of maintenance. Fourth, the guideline encouraged the use of expert panels to use their expertise in other aspects of the Maintenance Rule, beyond that of SSC risk assessments, such as the required periodic evaluations. This perhaps would help plants justify to themselves to invest in permanent panels. Fifth, for new plants, since determining baseline performance criteria, for placement in (a)(2), requires operating history, the guideline recommended basing criteria on industry operating experience such as that from similar plants. Here is an example of movement that would incentivize the capture and sharing of operating experience. Sixth, to address this issue of unexamined system trains masking functional degradation, the guideline was explicit, "Risk significant systems and standby systems that have redundant trains should have goals established for the individual trains."[292] Finally, the guideline made several recommendations to thoroughly stress the importance of risk assessment of maintenance activities that affect plant operations to include on-line maintenance — where the reactor is at power. The guideline explained this as: "Actions to manage risk generally are directed at properly controlling

[292] Nuclear Energy Institute 1996, 28.

out-of-service time and maintaining configuration control to ensure defense-in-depth when certain systems or equipment are made unavailable."[293] Here we see recognition that failed SSCs cause system outages (requiring maintenance) as do SSCs taken out of service (for required maintenance).

NRC Regulatory Guide 1.160 Rev2

As was normal procedure, after the NEI (the industry's advocate) adjusted its 93-01 guideline with the April 1996 Revision 2, the NRC worked to make corresponding adjustments to its 1.160 regulatory guide. These changes would provide feedback, or fine tuning adjustments, for industry's 93-01 rule implementation guideline and formally endorse it; the NRC's "iterative process." With the MBRIs just underway (beginning in July 1996) the NRC chose to release a draft (DG-1051, August 1996) of their proposed Revision 2 to RG 1.160 and postpone publication of the final version until they had completed an initial set of MBRIs. They were fast tracking rule implementation by simultaneously providing an informal endorsement to 93-01 Rev. 2 (draft RGs are not official), as the industry worked through practical Maintenance Rule deployment issues, while awaiting feedback from the MBRIs for incorporation into the final Revision 2. The NRC had provided the utilities with an accurate (although unofficial) look at what the final guide would most likely be. In DG-1051 they stated that, "This regulatory guide is being revised to endorse Revision 2 of NUMAR 93-01…which has been updated by the

[293] Nuclear Energy Institute 1996, 42.

Nuclear Energy Institute."[294] The draft guide's overall regulatory position was that, "Revision 2 of NUMARC 93-01…provides methods that are acceptable to The NRC staff for complying with the provisions of 10 CFR 50.65 with the following provisions and clarifications."[295] Those provisions and clarifications were detailed in the previously discussed NUREG-1526, *Lessons Learned from Early Implementation of the Maintenance Rule at Nine Nuclear Power Plants.*[296] The base had been established and the in-progress MBRIs were providing additional input for final adjustments to the licensees' and the regulators' thinking and their methods of implementation and oversight. With several months of the MBRIs completed the NRC published Revision 2 of RG 1.160 in March 1997 and continued with the inspections for another sixteen months, completing them in July 1998.

Maintenance Rule Implementation Recommendations

With the MBRI's completed, the NRC laid out high-level recommendations for changes and improvements to how the licensees were approaching implementation of the Maintenance Rule. First, the NRC did conclude "that the requirements of 10 CFR 50.65 [could] be met using NUMARC 93-01 as endorsed by RG 1.160; however, some weaknesses in these guidance documents were noted."[297] The NRC endorsed 93-01 Rev. 2 with its issuance of RG 1.160 Rev. 2 and then observed, during the MBRIs, how

[294] U.S. Nuclear Regulatory Commission 1996, 3.
[295] U.S. Nuclear Regulatory Commission 1996, 10.
[296] U.S. Nuclear Regulatory Commission 1995.
[297] U.S. Nuclear Regulatory Commission 1999, 3-1.

the licensees were executing the industry's plans as laid out in 93-01 and with RG 1.160's parallel guidance. The NRC gave several recommendations for improvement: 1) SSC risk significance determination using PRA. This included cautions concerning PRA modeling methods where some instances of PRA analysis could inadvertently remove failure sequences for high-safety-significant (HSS) SSCs. It was also noted by the NRC that they were not entirely confident in the quality of sites' PRAs since they had "not been assessed through peer or industry reviews."[298] Interestingly, this was not purely a criticism of the licensees' methods, but an observation of the nuclear power system's (both industry and the regulator) overall maturity in the use of PRA. The NRC candidly said, "This issue on PRA quality is addressed in ongoing NRC and industry initiatives to identify requirements for PRA standards in a PRA certification process."[299] A clear statement that they were still working through the implementation of PRA technologies, 2) that both the NRC and industry must early on commit the resources for "risk-informed, performance-based regulatory activities."[300] With extensive risk assessments and non-prescriptive, locally produced, performance-based processes, not being ready-made, initial implementation requires a great deal of effort and management support by the licensees *and* the NRC, 3) expanded use of expert panels beyond that of their concentration on PRA. The NRC saw that expert panels could be effective in other areas of Maintenance Rule operations such as scoping, establishing goals and performance criteria, and evaluating the movement of SSCs between (a)(1)

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[298] U.S. Nuclear Regulatory Commission 1999, 2-14.
[299] U.S. Nuclear Regulatory Commission 1999, 4-1.
[300] U.S. Nuclear Regulatory Commission 1999, 4-1.

and (a)(2), 4) that licensees place emphasis on the continual self-evaluation of the effectiveness of maintenance programs and that they "remain as living programs that demonstrate the effectiveness of maintenance activities in improving overall plant performance,"[301] and finally, 5) that the NRC should also maintain the Maintenance Rule as a permanently operating program by periodically holding public meetings and workshops with industry to inform updates to Maintenance Rule guidance. The Maintenance Rule was to be kept living through its own formal life-cycle.

Conclusion

The Maintenance Rule, 10 CFR 50.65, was the initiating event for implementation of nuclear power plant maintenance programs, but it did not act in isolation. The Rule, in combined implementation with the industry's NUMARC 93-01 Guideline, and the NRC's 1.160 Regulatory Guide, established the legs of, what I could call, the nuclear maintenance technology triad. This is the technical supporting system built and maintained to sustain the continued safe functionality of nuclear power plants' structures, systems, and components. It became the system that maintained the life of the plants. The system was implemented by the NRC and the nuclear industry, in a manner much like what I have experienced with other technologies, through a progression of education, training and operational experience.

The formal process of publicly proposing a rule provided a structure to mutually educate both the nuclear industry and the NRC on the new paradigm of a

[301] U.S. Nuclear Regulatory Commission 1999, 4-2.

comprehensive maintenance program; a program that went far beyond corrective fix actions that had traditionally formed the bulk of maintenance. In the context and mechanics of rulemaking the NRC explicitly defined maintenance for the nuclear industry and themselves as the regulator. Maintenance was now to be constructed and viewed, not as loosely coupled individual corrective actions, but as a systemic program with preventive and predictive maintenance as the new defaults. To get there, it was a back and forth conversation between the NRC and the industry. The NRC published their thoughts and the industry responded with commentary that the NRC, in turn, used to shape the Rule. It was a jointly performed construction with the NRC encouraging the industry to assist them in building something practical and workable. They were creating and educating themselves on the structure of a performance-based regulation, that required the NRC to define end-of-the-day performance requirements and the industry to determine how they were going to achieve those requirements. The rule construction was the higher level education. To put that education to practical use required process level training where the industry and the NRC would learn how they were going to jointly implement the Rule.

The joint training, how things were going to be accomplished, was documented in the closely coupled NUMARC guideline and the NRC Regulatory Guide. As we have seen the guideline was where the industry published how it was going to achieve the Maintenance Rule requirements, thus providing a basis for training of their plant management and maintainers. It also trained the NRC inspectors on what they could expect to see the maintainers to be doing as they worked to implement the Maintenance

Rule. It was obviously essential that both maintenance personnel and inspectors were working from the same technical standards. From my own experience, maintaining military aircraft systems, I know that it is also essential for the maintainers being inspected to be explicit in performing their maintenance activities according to maintenance guides. If the execution of a properly accomplished procedure is not evident to the inspector there can be suspicion that the procedure was not done correctly, even if the end-state is a properly performing system. The guideline and the regulatory guide were providing the framework for indicators of maintenance legibility between the maintainers and the inspectors. Knowledge of the system and confidence in it are fundamental elements of a safely and reliably operating system. To emphasize that point I can relate further personal experience with maintenance.

On the U.S. Air Force flightline my team and I had just finished loading and configuring a jet fighter aircraft with weapons (bombs, missiles and ammunition). The pilot walked up, wearing her flightsuit and carrying her helmet:

She asked me, “Load done? Jet good?”

I flipped through the last few pages of my loading checklist and answered, “Yes, ma’am, bombs, bullets, and missiles. Bomb fuzes set. Everything armed. Post-load complete.”

“Great! Thanks!” she replied as she began walking the jet wing-tip to wing-tip, performing her own pre-flight checks of, now, her jet.

That brief interaction between a maintenance weapons loading team and the pilot of a fighter jet demonstrates the result of a formally implemented maintenance system of education, knowledge and, ultimately, confidence. The pilot knew what technical guidance the maintenance team had used in the form of checklists for aircraft preparation, electronic functional checks, and weapons loading. She knew that when I told her, "Post-load complete," that I had performed a detailed post loading inspection of the weapons and the aircraft to ensure all systems and components were correctly configured and ready for flight. I knew what she would be looking for during her pre-flight inspection; the results of my maintenance loading activities. She had confidence that everything she had visually inspected would be in order. Furthermore, she had confidence that I had performed the electronic checks correctly because she knew I had been trained and had used step-by-step procedural checklists. There was also a final administrative check where she looked to see that I had literally signed my name to paperwork documenting the functional checks and weapons loading. The maintenance guideline and the regulatory guide had set the conditions for these same types of maintenance performance and inspection activities in the commercial nuclear power environment. How were those conditions transformed into practicable implementations?

Practical, actual world implementation was developed and learned with practice, and operating experience. We have seen that the NRC and industry did not simply write the Rule and guidance documents, distribute to power plant operators, and return to their desks. The Rule and guides were not complete until used and tested, in other words, practiced, learned, and modified/corrected as informed by functional feedback. The early implementation period and follow-on baseline inspections showed that this new Maintenance Rule technology was a functional framework. These assessments evaluated the effectiveness and "ergonomics" of scoping, risk determination, goal setting, and monitoring, by plant maintainers and a shift to mechanisms that emphasized predictive and preventive maintenance over reactive repair actions. Here was demonstrated that the NRC and industry understood that operating experience, with a foundation of education and training, is fundamental to the successful implementation of a new technological components and critical for safe deployment in a nuclear system.

With deployment of the Maintenance Rule and its implementing guides, the NRC and the industry had created the starting basis for the nuclear maintenance regime. A government mandate was in place as a performance based regulation that allowed the industry the flexibility to locally construct maintenance methods. It forced the creation of system and component monitoring, predictive and preventive maintenance technologies and, most importantly, comprehensive maintenance program thinking throughout the commercial nuclear community. It was so significant that NRC historian, Dr. Thomas Wellock, characterized the Maintenance Rule as one of the "top events in regulatory history." [302]

[302] Wellock 2018, 1.

Chapter 5
Reworking Maintenance

In this chapter I extend my examination of Maintenance Rule implementation by looking in detail at its lower level technology that engages directly with the plant's maintenance program and the inspectors; the NRC's Inspection Procedure (IP). Not only do I look at the IP's written working mechanisms and their utilization, I also relate the perspective of nuclear engineers who have real world experience with the inspections and how they are actually executed. Additionally, I discuss the execution of maintenance inspections and maintenance activities and how they create nuclear power plant working knowledge. I go on to explore my thinking on how this maintenance knowledge assists in constructing a nuclear operational principle for power plants and, ultimately, provides means to indicate the end-of-life of power plants.

Inspection Framework - Tools

The NRC uses an extensive manual of inspection for all aspects of its regulatory monitoring and compliance oversight. It is a tool of administrative instrumentation utilized to gain and maintain situational awareness and understanding of the licensee's activities, plant condition, and regulatory compliance. For maintenance activities, this includes assessing how effectively the licensees are implementing the maintenance rule. The NRC inspection manual contains over two-hundred chapters and related appendices. Each chapter describes and defines a specific inspection program and its inspection procedures. Overall there are nearly four-hundred inspection procedures that are used to provide inspection objectives, guidance, and requirements to the inspectors. For the Maintenance Rule, the NRC developed, and made available, in January 1994, a draft maintenance inspection procedure (IP) which was tested for its effectiveness during the plant pilot inspections conducted by the NRC from September 1994 to March 1995.[1] Were the procedures effective in allowing the NRC to determine how effectively the station licensees were implementing the Maintenance Rule? At the end of the nine site pilot program, the NRC simply concluded that “the draft inspection procedure can be used to monitor the implementation of the rule.”[2] Two months after the results of the pilot evaluation were published, the NRC finalized and issued IP 62706, Maintenance Rule, dated 31 August 1995.[3] The NRC had pilot tested and readied its IP for the Maintenance Rule’s operational rollout on 10 July 1996. The NRC knew how to inspect, and industry knew what to expect.

For the next year the industry continued to work toward full implementation with current versions of NRC RG 1.160 and NUMARC 93-01 as overall guides, and the new NRC IP 62706 informing them how to shape their implementation activities in more detail. Once the Rule came into effect, the NRC initiated its two year program (July

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[1] U.S. Nuclear Regulatory Commission 1995.
[2] U.S. Nuclear Regulatory Commission 1995, 33.
[3] Taylor 1996.

1996 to July 1998) of Maintenance Rule Baseline Inspections (MBRI) to evaluate how well the licenses were implementing the rule as they were now legally required.[4] These and earlier MRBI results informed updates to NRC RG 1.160 and NUMARC 93-01 which in turn pushed the update and issuance of Revision 1 of IP 62706, dated 31 December 1997.[5]

The NRC now had in its Maintenance Rule toolkit: an Inspection Procedure and a Regulatory Guide both deliberately shaped with actual OE from the working implementation of the Maintenance Rule. This working process was deliberate as indicated by NRCs comment that, "until full implementation of the rule is observed, it is difficult to determine whether the guidance documents and inspection procedures have sufficient details to ensure compliance with requirements."[6] The NRC had a functional tool for Maintenance Rule implementation inspections. How did it work?

As we have seen, for use during the pre and post implementation of the Maintenance Rule, the NRC developed and used IP 62706. Like its direct and to the point title, "Maintenance Rule," IP 62706 was the tool that enabled NRC inspectors to verify that 10 CFR 50.65 (the Maintenance Rule) had been programmatically implemented by the plant licensee. The IP was the NRC's instrument to examine a plant and indicate if the licensee had put into place (implemented) mechanisms that would meet the requirements of the Maintenance Rule's primary paragraphs: (a)(1) -

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[4] U.S. Nuclear Regulatory Commission 1999.
[5] U.S. Nuclear Regulatory Commission 1999.
[6] U.S. Nuclear Regulatory Commission 1999, 2-8.

Goal Setting and Monitoring, (a)(2) - Preventive Maintenance, and (a)(3) - Periodic Evaluation.

For (a)(1) this was the verification that the licenses had implemented monitoring of SSCs, had established goals, and was taking corrective maintenance action when an SSC was not meeting a goal. Under paragraph (a)(2) the plant needs to demonstrate that it could keep SSCs fully functional with preventive maintenance (PM) or the SSC was inherently reliable or could be run to failure without degrading safety. In (a)(3) the licensee needed to show it had developed self-evaluation methods to periodically assess its own maintenance rule activities. Similarly, the licensee had to demonstrate it was aware that its maintenance program should be constructed to ensure that, "maintenance is appropriately balanced against the objective of minimizing unavailability of SSCs due to monitoring or preventative maintenance activities."[7] That was the large picture, essentially a recap of the Maintenance Rule, presented to NRC inspectors. The inspection procedure also provided some additional framing for the inspection process.

The IP included guidance that called out a few key points associated with the inspection areas. To being with, the inspection requirements in IP 62706 could be tailored in their use; not all inspection steps needed to be performed at every inspection. If there was a problem area, for example in preventive maintenance, the inspectors could focus on that deficient area and leave other areas for another time. The inspectors were also to generally expect the licensees to comply with the Maintenance Rule using methods described in NUMARC 93-01 and NRC RG 1.160. But, the

[7] U.S. Nuclear Regulatory Commission 2000, 2.

inspectors were reminded, this was not mandatory. The licensees could legally use methods other than outlined in the industry and NRC guides, but would need to "demonstrate that those methods satisfy the requirements of the rule."[8] The Maintenance Rule (10 CFR 50.65) was the only source for requirements.

All other sources of related information described not requirements, but "acceptable methods" to comply with the requirements. Alternate methods were thus acceptable, but the licensee had to demonstrate to the inspectors that they could satisfy meeting the rule requirements. Concerning SSC preventive maintenance, while monitoring of SSCs under (a)(2) is not required the IP pointed out that the licensee needed to establish acceptable methods " to verify that preventive maintenance is effective."[9] The inspection procedure document also included a list of applicable background references and even a few words about the implementation history of the rule. It concluded by stating that a complete inspection effort would take five to six inspectors approximately 600 inspection hours to complete: "five inspectors for 3 weeks performing 1 week of inspection preparation, 1 week on-site, and 1 week of inspection documentation."[10] Even with a considerable number of work-hours involved, IP 62706 was a programmatic assessment of implementation of the rule and not of how to examine the effectiveness of maintenance execution itself. The draft maintenance inspection procedure called for an assessment of maintenance effectiveness.[11] This was in addition to verification of the maintenance rule, but the apparent emphasis of the

[8] U.S. Nuclear Regulatory Commission 2000, 3.
[9] U.S. Nuclear Regulatory Commission 2000, 5.
[10] U.S. Nuclear Regulatory Commission 2000, 7.
[11] U.S. Nuclear Regulatory Commission 1994.

early pilot (NUREG-1526) and baseline (NUREG-1648) inspections was rule implementation. Both NUREG reports focused on the licensees' methods of implementation, as framed in NUMARC 93-01 and endorsed in RG 1.160, with little detail concerning assessment of maintenance execution. That emphasis was to be expected, during the initial assessment of Maintenance Rule implementation, since those early activities were effectively the construction of the maintenance program infrastructure, before it was put into fully functional operations. Once the infrastructure was evaluated to be in place and operationally ready the NRC refocused its efforts to ensure it had the proper tools to assess how the maintenance rule affected maintenance effectiveness. Inspection procedure, IP 71111.12 - Maintenance Effectiveness, was developed and the maintenance effectiveness section was removed from IP 62706.

Inspection Procedure, IP 71111.12 - Maintenance Effectiveness - falls under Part 7100, in the Operations Chapter of the Inspection Manual and was constructed to provide "independent oversight of licensee maintenance effectiveness including MR activities, work practices, and common cause issues."[12] Its objective was to guide NRC inspectors through a plant evaluation to assess if the licensee was practically performing effective maintenance that would ensure compliance with their implemented Maintenance Rule program. This was to be accomplished through sampling by reviewing "8 to 10 maintenance effectiveness performance issues a year with emphasis on high-risk-significant issues."[13] The inspection procedure contained detail points of

[12] U.S. Nuclear Regulatory Commission 2002, 2.
[13] U.S. Nuclear Regulatory Commission 2002, 1.

evaluation to assess how the licensee was handling SSC performance and condition problems as framed by the maintenance rule in its areas of monitoring, preventive maintenance and periodic evaluation. The points of evaluation included: 1) Were SSCs actually available and performing reliably? Were documented SSC failures mapping to the licensee's Maintenance Rule monitoring and tracking program for action? Within these failures, were adverse trends recognized and engaged with? 2) Was corrective action, required by the maintenance rule, being effectively performed and was it taking into account industry standards and informed by operating experience? 3) Assess the correlation of SSC functional failures to licensee goals or SSC performance criteria. Were SSCs properly correctly classified in (a)(1) or being effectively maintained under (a)(2)? The procedure gave the inspector a list of potential plant sources to examine for information to engage with the above areas (as detailed below):[14]

- Operating logs (manual and automated)
- Plant event reports/condition reports
- Technical specification action statement logs
- System or component work order history
- Safety system unavailability and unreliability performance indicator data
- Other reliability and availability data (MR, PRA, INPO/WANO)
- Corrective action program documents
- Operability evaluations or non-conformance reports
- Temporary system modification documents
- Maintenance (or component) history databases
- System "health" reports

[14] U.S. Nuclear Regulatory Commission 2002, A-2.

- Predictive maintenance test or condition monitoring results (e.g. thermography, lubricating oil analysis, vibration analysis, other in-service test results)
- Maintenance Rule program documents
- Plant walkdown observations and plant status information
- Licensee personnel interviews
- Information discussed at licensee meetings
- Industry operating experience (IOE) information

From these sources the inspector was to "select potentially risk-significant issues for detailed review."[15] The sources would also provide an initial understanding of how the issue was identified, its failure history, work practices, what may have contributed to the problem, effectiveness of corrective maintenance, use of industry OE, and preventive maintenance employed or revised. With that background knowledge the inspector would dive deeper and investigate directly, beyond examining records. For example, the inspector would determine the extent of the problem and its frequency, assess if the issue affected other systems, observe associated work practices being carried out (watching maintenance) evaluate related training, and determine if the problem had previously been inspected.[16] This process took the inspector from the paperwork to the real work.

What did that real work really look like? After TMI-2, the NRC incorporated two resident, government, inspectors at each plant site. As NRC technical representatives, they watch (over the shoulder) plant activities to ensure the licensee is safely operating and maintaining the plant and meeting the requirements of regulatory rules. Their

[15] U.S. Nuclear Regulatory Commission 2002, A-2.
[16] U.S. Nuclear Regulatory Commission 2002.

normal routine is framed in the NRC’s baseline inspection program that covers all aspects to the plant activities to include maintenance rule compliance checks.[17] The resident inspectors have discretion on what they examine over a year as long they “inspect the number of samples specified by the baseline inspection procedures because the baseline program provides the insights necessary to assess performance.”[18] When I asked an NRC engineer about how or if inspectors and plant personnel planned or prepared for inspections this is how the engineer described it:

If there's something interesting coming up, say, like an emergency diesel generator functional equipment group window…where you're looking at three different maintenance groups: the electricians, the instrument control individuals, and mechanics, all getting together to do one maintenance activity such as taking a diesel out of service, which is risk significant for most plants.

Look at the maintenance activity coordination between the different maintenance groups and you can generally get a kind of holistic view [to] look at the equipment tagging…follow the operator and watch them tag out the diesel…and that's a specific sample for another inspection procedure...and then…look at the risk assessment that they do to take out this piece of equipment...and what’s the risk management action they put in place before they do it?

That's part of the maintenance effectiveness. They can look at, once it's returned operable, the surveillance control and that's a different sample from a different inspection procedure. So, there’s, I think, it's not really a supplemental inspection where the licensee is going to get notification that we're coming at this specific time, with this many people, and these are the things we’re going to look at. It's part of the baseline inspection procedure...where the resident inspector is there every day.

They attend the daily meetings. They'll look at some risk significant work. They'll figure out what they want to look at. And then they'll pick their samples based on those types of things. So, there's not...I

[17] U.S. Nuclear Regulatory Commission 2013a.
[18] U.S. Nuclear Regulatory Commission 2013a, A-3.

wouldn't say there's necessarily a preparation…by either side, the regulator or the licensee, for that type inspection because it's ongoing all the time.[19]

The inspection is integrated into the workings of the plant's activities. It is not a singular event. The eyes of the inspector are continually examining both the routine and the exceptions, with interesting occurrences or events primarily getting their attention as explained by a licensee engineer:

It's all part of the resident baseline inspection program. They may, I think once a year, and it's up to them when. Typically, they select, maybe one system and then they take a look. Are we following our procedures? Are we collecting the right data? Is the data accurate? If we exceed a performance criteria are we doing the evaluation to see if it should go into (a)(1)? Those are going to be pretty routine. Very occasionally they'll see a piece of equipment fail and you may see a 50.65 violation for not having that equipment in the scope of the rule. Those typically aren't driven by an inspection…they're driven by some plant event. The resident then looks at. It's become pretty much routine from a maintenance rule inspection.[20]

The NRC was aware that the rationalized structure of an inspection procedure, or the thinking of an inspector, would not consistently align with the realities of a working plant. In IP 71111.12 they candidly stated that, "In view of varying inspector experience and widely varying licensee practices, the following discussions address some of the more complex (and historically contentious) MR issues based on the collective inspection and enforcement experience of resident and regional inspectors and headquarters staff."[21] The "following discussions" was a surprisingly verbose discourse (few truncated paragraphs and bullet statements) that stepped the inspector through

[19] Interviewee 006 17 August 2018, 0:30:12.2.
[20] Interviewee 007 24 August 2018, 0:47:28.9.
[21] U.S. Nuclear Regulatory Commission 2002, A-4.

two process flow charts and a range of assessment situations. The flow charts were guides for assessing both Maintenance Effectiveness and Periodic Evaluations (PE). The described situations were those that an inspector could very well encounter during plant inspection tours and that, the NRC apparently expected, would require some interpretive analysis.

The following excerpts demonstrate how the NRC was making legible the nuances of regulatory inspection to both its inspectors and the nuclear industry:

> The inspector should consider maintenance-related contributing factors in a broad sense, not limited to work practices or other activities of maintenance staff alone.[22]

Here was emphasis, to shape the thinking of the local NRC inspectors, on a primary reason for the existence of the Maintenance Rule; it was developed to effectively force the construction of formal, and widely encompassing, maintenance *programs.* Programs that included all manner of supporting maintenance activities from up-stream procurement and training to down-stream failure trending and data analysis. Maintenance was now defined to be considerably more than simply turning wrenches.

> These maintenance support activities can be viewed as part of a more comprehensive concept of maintenance, and preventive maintenance in particular.[23]

The concentration on preventive maintenance, as the preceding excerpt states, meant the shift from reactive wrench-turning to a philosophy of maintenance that anticipated failures with data collection, analysis, and thinking. Preventive maintenance was aimed

[22] U.S. Nuclear Regulatory Commission 2002, A-5.
[23] U.S. Nuclear Regulatory Commission 2002, A-6.

to prevent SSC failure and also, as far as possible, prevent the need for corrective maintenance.

> Operator error, for example, committed in direct support of maintenance (e.g. clearances, valve or equipment lineups, etc.) may require a failure to be deemed an MPFF by the licensee's program.[24]

Here, with the commentary on operator actions, the NRC recognizes that, at least at some sites, the licensees are truly looking at maintenance as an all-encompassing program or system. The typical divide between operations and maintenance appears to have been not so distinct, with the licensee recognizing that plant operators are involved with maintenance and its success (or failure). It is interesting to note that the distinction is almost always explicit with the standard reference, "Operations *and* Maintenance" or O&M (emphasis added).

> Treatment of very long fault exposure time resulting from long-standing latent deficiencies (e.g. design deficiencies) depends on the circumstances…it may legitimately be judged not to reflect adversely on current maintenance effectiveness or on other aspects of the "health" of the affected SSC(s).[25]

With the above description of undiscovered or latent deficiencies comes another recognition that things may not necessarily be what they seem with a cursory look. A problem that has the capability of affecting SSC performance may have never been made legible either through known direct inspection methods or from industry OE. That lack of legibility, or understanding, of the system is not necessarily to be attributable to poor practices by the licensee. If the licensee takes the proper corrective action to

[24] U.S. Nuclear Regulatory Commission 2002, A-6.
[25] U.S. Nuclear Regulatory Commission 2002, A-7.

address the deficiency the NRC would not necessarily charge the license with unavailability for the SSC.

> Repeated failure to meet goals may be indicative of inadequate corrective action. However, note that failure to meet (a)(1) goals is not, by itself, an MR violation. However, failure to take timely and adequate corrective action when (a)(1) goals are not met (corrective action that addresses the cause(s) of the problem(s)) may constitute a 50.65(a)(1) violation (depending on the circumstances.[26]

The above is a reminder, for inspectors, that Maintenance Rule goals are *in-process* performance measures. They are established, adjusted as more is learned, and used by the licensee to work toward the development of a set of maintenance activities that would move the SSC to an (a)(2) or preventive maintenance condition.

The inspection procedure also provided example, for the NRC inspectors, maintenance inspection evaluation scenarios. The following is a usefully informative excerpt from one such use case:

> In practice, when licensees consider putting the affected SSC/function in (a)(1), but can justify not doing so by reason, for example, of the root cause being either corrected or unrelated to the equipment itself (e.g., personnel issues only), then they may be deemed to be in compliance with the MR while allowing the affected SSC/function to remain in (a)(2) status. However, if the circumstances warrant monitoring the affected SSC/function under (a)(1), and the licensee commences monitoring under (a)(1) within a reasonable amount of time, and takes prompt and adequate corrective action in case goals are not met, there has, thus far, been no violation of the MR in this scenario. Therefore, when the inspector reviews the circumstances described above, and determines that the licensee has not yet complied with the MR, the inspector must then determine whether the time that has passed since the licensee's first opportunity to comply is excessive, in which case, a violation may be identified.[27]

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[26] U.S. Nuclear Regulatory Commission 2002, A-10.
[27] U.S. Nuclear Regulatory Commission 2002, A-13.

In this example the NRC is displaying the workings of the Maintenance Rule's system of compliance and its system of evaluation. It provides an example that, while not specific to a particular SSC, is representative of a not-uncommon event that can be generalized to a wide range of plant domains. It depicts the transactions involved when working within the Maintenance Rule framework. It shows the flow of those transactions as they transition between (a)(1) and (a)(2). The narrative describes the observations of the inspectors and their potential directions of deliberation as they make assessments. It shows that the inspectors have some latitude of discretion in how they assess a compliance or non-compliance decision; evident in language such as, "within a reasonable amount of time" and, "whether the time that has passed since the…first opportunity to comply is excessive."[28] The example also presents, in related language, the potential actions and thinking of the licensees as they respond (or do not respond) to events and inspectors' evaluations. Wording such as, "takes prompt and adequate action," or "the licensee has not recognized this" and, "justify not doing so" were used by the NRC to describe and characterize for the inspectors what they may encounter at a plant in the course of their duties.[29] The IP was providing guidance for inspectors as they carried out the mechanics of their Maintenance Rule activities and it was also shaping their thinking on what to expect when they encountered the effects of the rule as it was introduced into the maintenance system.

Finally, there are indications that the regulatory Inspection Procedure itself became a tool to move the implementation process along at a faster than normal pace

[28] U.S. Nuclear Regulatory Commission 2002, A-13.
[29] U.S. Nuclear Regulatory Commission 2002, A-13.

and helped the industry adjust to working with a performance, or results-based regulation. Since the Maintenance Rule was results-based it contained little detail or prescribed actions, as to *how* the results were to be obtained. This was not a normal situation for either the industry or the NRC. The Maintenance Rule was one of the first performance-based rules the NRC had deployed so neither the industry nor the NRC had significant implementation "OE" with this type of regulation. The industry had little experience with establishing their own performance criteria, to achieve the rule's required results, since in the past it would have been constructed and prescribed by the NRC. The NRC also had little regulatory experience with the results-oriented approach where it had historically focused on process. With little to inform their actions, the industry needed to quickly determine an effective approach to constructing an acceptable (to the NRC) maintenance program that would meet the requirements of the Maintenance Rule.

The industry nudged the NRC to reveal their thinking concerning what implementation methods would be in the range of acceptability. The NEI asked the NRC for early reads of their draft maintenance inspection procedure to guide them as they developed their guideline; "They wanted to use the inspection procedure to address details, not in the rule itself."[30] Further, in March 1994 the NRC held a public workshop with industry to review their draft inspection procedure where the NRC explained the IP's use and the NRC's "expectations about implementation of the rule."[31] The inspection procedures framed, for industry, what the NRC wanted to see; what they

[30] U.S. Nuclear Regulatory Commission 1995, 3.
[31] U.S. Nuclear Regulatory Commission 1995, 5.

did not make explicitly evident directly in the performance-based Maintenance Rule. Without changing the regulation, the industry had effectively shifted the performance-based Maintenance Rule toward a more prescriptive rule; an adjustment that made for easier implementation while still allowing for flexibility. One of my interviewees made this clear to me when talking about the paucity of guidance and detail in the Maintenance Rule:

> It's performance based...it's outcome oriented as opposed to being prescribed...do x, y and z. Cause, really, when you write a rule it's hard to know exactly what needs to be done...you just know what the outcomes are to be. So the maintenance rule…it gives you high level requirements to meet. The difficult part with that is...it's hard...performance based regulations...it's kind of cryptic…if you read the rule it's kind of hard to understand what the heck you have to actually do...so it's kind of open...so it's hard to enforce from the regulator side.[32]

As with the maintenance effectiveness guideline (NUMARC 93-01), the industry was, as I would describe it, decrypting the performance indicators for both themselves and the NRC. The decrypting was extensive, and it was recognized by the cipher breakers:

> It's funny, they write a rule...a couple of paragraphs and we [the industry] spend a hundred pages to fill in all the gaps...what the rule means.[33]

The IP had become a translational knowledge interface between the NRC and industry. It made evident the required technical details of an effective maintenance program and also made legible (for industry) what the NRC was thinking and (for the NRC) what the industry was doing. Here was detailed working knowledge of working nuclear power plant maintainers and detailed regulatory knowledge of regulating

[32] Interviewee 002 25 May 2018, 0:05:11.
[33] Interviewee 002 25 May 2018, 0:05:11.

government inspectors. These knowledge producing activities and relationships were foundational elements of a maintenance environment. *Knowing* a nuclear power plant system is fundamental to its effective maintenance and its life.

The New Normal Maintenance

Unlike a fossil fuel powered plant, in the event of system or component failure or an emergency situation, a nuclear plant cannot be completely turned off, or shutdown; at least not immediately. While the fission reaction can be halted by dropping control rods into the core the fuel rods still produce decay heat that require continual cooling water flow. Without reliable constant cooling around the fuel rods, the cooling water will eventually evaporate, uncovering the reactor fuel which will soon lead to the rods melting and the potential release of radioactivity into containment or, in a worst case, into the outside environment. Also, cooling is required for used rods, stored in spent fuel water pools that have been removed from the reactor during refueling operations. Like the rods in the reactor itself they must be constantly covered by cooling water to prevent melting for at least one year before being able to be moved to dry cask storage.[34] With these operational requirements and hazards in mind it is clear that the reliable functioning of a nuclear power plant's SSCs are critical to safe operations; everything must work.

The plant operators and engineers must *know* the operational condition of SSCs, and with a higher degree of certainty for those SSCs that provide critical safety

[34] U.S. Nuclear Regulatory Commission 2019c.

functions such as core cooling — *the* critical safety function. Not only must the current condition be known, but plant operators must also know the *future* condition of SSCs. In other words, they must have the ability to predict SSC failure well in advance of the failure; practical, prescience knowledge for preventive maintenance actions that keep the SSC safely and reliably running.

As presented in the Chapter 1 discussion on the life of large technological systems, here we see the critical importance of the Maintenance Rule to nuclear systems. It constructed and aligned maintenance to integrate into the thinking of the nuclear operational principle and also to become a normal component of its technological configuration. That normal configuration of a nuclear power plant requires a robust knowledge producing component. Nuclear maintenance programs, constructed to meet the requirements of the Maintenance Rule, became that knowledge producing technological component. Maintenance was reworked as knowledge.

Maintenance as Knowledge

Being a knowledge producer, the maintenance component brought new legibility of the nuclear system to its operators. As both industry and the NRC worked toward implementing the Maintenance Rule they reworked maintenance from being a reactive, point-in-time action to a comprehensive, end-to-end program of monitoring, analysis, prediction, and continuous actions. In the normal configuration of a fossil fuel power plant maintenance was primarily a corrective action; something performed in response to an SSC failure. It was a break-fix activity, generally with little formal analysis of the failure in order to establish root cause, or to determine if it indicated a trend that could predict future failures. It was not focused on prevention of failure; only how to react. Corrective maintenance *was* maintenance.

While corrective maintenance remained critical in both thinking and action (SSCs still fail) the goal of a shift to the development of an established maintenance program was to prevent failures and to minimize the need for corrective maintenance actions. As maintenance activities, continuous monitoring and analysis of SSC conditions and performance, provided a window into knowing and understanding the system. Maintenance became much like a telemetry or instrumentation component. It was becoming operationalized and providing information and knowledge similar to control room indicators, but with a significant difference.

Control room instruments indicate the *current* status and functioning condition of plant systems and components. They show such system information as control rod positions, pressures, voltages, coolant flow, valve positions, temperatures, alarms and enunciators, and radiation release indications. The operators have situational awareness of only the present; what is happening now or happened in the immediate past. They have lagging knowledge as to the condition of the plant. In contrast, a well implemented maintenance program, as an integral technological component of a nuclear plant, can provide what I would describe as, *leading-knowledge* of plant conditions. The maintenance program's monitoring and analysis functions continually examine and document past plant conditions and performance levels. Through methods and techniques such as radiography, magnetic particle testing, penetrant testing, thermography, electrical functional checks, vibration analysis, root-cause-assessment, trend analysis, and probabilistic risk-assessment (PRA), maintenance can understand the condition of system components *before* they fail and predict their future failure. With maintenance as knowledge instrumentation the plant engineers could then pro-actively act with preventive maintenance actions. Preventive maintenance is what I would describe as *thinking-maintenance*. It is cognizantly planned (pro-active), controlled, and commanded by the maintenance personnel. It is upstream from a degraded or failed safety system. In comparison, corrective maintenance could be reasonably called *physical maintenance* since it most often requires physical interaction with the system, on the system's conditions which can be hazardous in themselves. It is unplanned (reactive), often with less control than desired, and at the command of the failed component. It is *downstream* from a degraded or failed safety system. A full maintenance program helps to build a complete plant control panel that not only indicates what has happened, but what *will* happen. It constructs knowledge, and displays it, to make future plant conditions legible. Maintenance had become an operational component of nuclear power plants. This new construct demonstrates how maintenance thinking had been reworked by the implementation of the Maintenance Rule.

As we have seen, under the fossil fuel operational principle, maintenance was only loosely coupled with the system. It was run *to* maintenance (the euphemism for run to failure) which practically locates maintenance as existing outside of the system. With the advent of The Maintenance Rule maintenance thinking began to shift from outside to within the system. Rather than thinking of maintenance as an external, point-in-time action with failures unexpectedly veering toward it, it was being reworked to be an internal system component. The system was now running *with* maintenance. This was in two senses: 1) the power plant was now operating with a maintenance program as an integrated system component, and, 2) it was operating simultaneously with maintenance, where maintenance is a continuous process that is moving along, a program structure of continual evaluation, trending analysis, future failure predictions, and preventive interactions. Running with maintenance creates system legibility that allows the system operators to make improvements not purely based upon actual failures, but upon predicted potential failures. Like a skilled and experienced aircraft pilot, they are operating *ahead* of the system; wings level, maintaining altitude and airspeed. Maintenance had been reworked in both thinking and in actions. Maintenance was now knowledge and an active, working component of the nuclear power system. The system was running with maintenance as a knowledge component.

From Leaking to Super Safe

"Is everything safe?" That was my opening interview question to the chief nuclear engineer of a major U.S. electrical utility who, unhesitatingly, and confidently, answered, "Super safe."[35] Prior to the Maintenance Rule the workings of a nuclear site's physical plant, and the thinking of the people working at it, were not conducive to this veteran engineer's superlative description. When I asked this same executive engineer to

[35] Interviewee 004 14 June 2018, 0:03:02.

compare the operations of fossil-fueled power plants to nuclear he characterized them just as many might when visualizing large, industrial operations:

You have leaks everywhere, water leaks, oil leaks, you name it, things are leaking...lighting's bad...it's not a good work environment. You go into a into a nuclear plant today...it's spic and span, it's spotless, there's no leak. It's a different world. I don't think there's another industry that has plants…the way we have.[36]

I inquired further about the thinking at fossil plants in the engineer's own company:

They don't. It's much different. It's much different. The brand new fossil plants are going to be nice for a while, but that don't have a maintenance standard. Their philosophy is if something breaks or something's not right, we'll send somebody out there to fix it or something…. I've been in our gas plants...and there's...it's just like night and day...it's not like a nuclear plant. Our nuclear plants...We put down the self-leveling paint on the floors so it's all nice and shiny and pretty. We put LED lighting everywhere so it's very bright. It's ah...it's a different world.[37]

The engineer described the break-fix maintenance philosophy and the overall lack of upkeep of fossil-fueled power plants in the past and, apparently, in the present. Two to four decades ago that appears to be the way nuclear power plants were also run; as just another dark and leaking industrial plant. That has been the common narrative, often heard in the United States since the TMI-2 accident with its stories of inadequately trained operators, ill maintained condensate polishers, misaligned feedwater valves, and maintenance tags blocking control room indicators.[38] What were some of the first-

[36] Interviewee 004 14 June 2018, 0:57:44.
[37] Interviewee 004 14 June 2018, 0:58:49.
[38] Kemeny 1979a; Rogovin and Frampton Jr 1980a.

hand observations, and passed down stories from that time in the nuclear industry; a time before the Maintenance Rule?

An industry engineer with nearly four decades of experience succinctly, and candidly got to the point when told me, "We weren't doing a whole lot of preventive maintenance...we were doing a lot of corrective maintenance."[39] In other words, the plants were breaking, the components and systems failing, without much thought to preventing the failures in the first place. Another nuclear engineer who is now employed by the NRC, recalled starting work for a utility in 2000, and hearing stories from people of how the plant used to be run and what was considered normal when operating a nuclear system:

> Yeah...talking to the operators...when I first got to Ginna [R.E. Ginna, Nuclear Power Plant, Rochester, N.Y.] talking to the operators....they were tripping once a week [laughs]....and they didn't think it was a big deal...it was...Yeah, we're starting the plant back up...it's...it's not that big of deal...we'll just fix whatever broke and start back up. It was kind of a laissez-faire attitude toward [laughs] the loss of generation, and safety, and those types of things.[40]

Failure had been normalized and even *incorrect* corrective actions were a normal part of the system of failure and unavailability as an NRC engineer pointed out:

> I started in 90...so...we heard stories that when there was a problem they just put duct tape around it [laughs]. A lot of those kind of stories...you heard because people would treat nuclear plants like fossil plants....growing pains in the nuclear industry...through the nineties...where a lot of them were shutdown for many years. They used to call it the NRC bad boy list.[41]

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[39] Interviewee 007 24 August 2018, 0:15:01.
[40] Interviewee 006 17 August 2018, 0:49:12.
[41] Interviewee 008 31 August 2018, 0:15:50.

As we have seen, in the 1980s the NRC began working to eliminate these improvised practices, or "duct tape thinking", (whether literal or not) through collaborative development and implementation of the Maintenance Rule. It was not only an effort to change failing practices, but an effort to co-change practices and maintenance culture.

> I think it was back to the cultural change...we really can't tolerate failures...we can't really have this stuff unavailable for days on end. It's important to safety...significant...we need to be more focused...and more efficient. I think it really was driven by the industry and us [NRC]. When you're in the business of making money...you can't be offline… Again, I think the culture change was how we thought about these facilities. Understanding that they're different...I think. That's where the culture [change] would occur.[42]

Here was an NRC engineer who was aware, historically and from experience, for the need to rework the industry's maintenance practices/culture. Further, even an industry engineer said oversight of maintenance needed "a bigger regulatory footprint" to force monitoring because "things that are not monitored…you don't put the management attention in…you don't do the improvements."[43] The Maintenance Rule became the big foot to push the commercial nuclear power industry out of its dark, dripping, and duct taped confines.

What were the stories and the views of those who witnessed the industry emerge from the pre-Maintenance Rule era? When asked, several nuclear engineers from both the NRC and industry had quite similar characterizations of the effects of the Rule. They all commented how it had reworked the industry's thinking and activities in maintaining their systems and how the reshaped philosophy contributed to understanding and engaging with system risk. The nuclear plants were safer and more

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[42] Interviewee 008 31 August 2018, 0:52:13.
[43] Interviewee 003 08 June 2018, 0:51:08.

available to generate electricity. An industry engineer straightforwardly described the effective work of the Maintenance Rule, and with a bit of candid humor:

> From my perspective the maintenance rule did two things. One, it brought forth the idea of risk into our maintenance...and to making sure we have defense in depth and when we take systems out or we take components out or we do any kind of maintenance on something we take a look at the risk of the plant...so from a safety...for the health and safety of the public...I think it's done a really good job of keeping risk in the forefront. Secondly, it's caused us as a management team...the leadership of this industry to focus on, 'Things that ain't right.' [laughs] Just to give it to you kind of straight.[44]

From the government perspective, an NRC engineer gave a practical view with references to objective indicators of improved performance. The engineer also added a frank and personal endorsement of the Maintenance Rule:

> I think the maintenance rule...there was a realization that proper plant maintenance was important to safety and making sure that these systems would actually operate and the type of anticipated operational occurrences that happened at the plant was very important...so...the genesis of the Maintenance Rule...helped with that. When you look at…the scram rates and the equipment reliability graphs from that era to this time you can see marked changes...in equipment reliability....there's a lot a different factors that came into that...but I do believe that the Maintenance Rule was one of those that was very effective in doing that and continues to this day. I think it's an important...thing that the plants do on a daily basis. I think it was a great program...to be honest...that's my personal opinion...[laughs].[45]

An industry engineer provided some actual reactor scram metrics that linked their decrease to improved component reliability as attributable to the Maintenance Rule. What was especially noteworthy, was that the engineer also stressed the balance-of-plant component maintenance that dramatically decreased scram rates:

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[44] Interviewee 003 08 June 2018, 0:51:08.
[45] Interviewee 006 17 August 2018, 0:45:42.

Scrams were very high...it was over...I think the average was 2.3 per year, per reactor in the 80s. Now it's 0.7 and so a lot of people attribute that to the maintenance rule. A lot of people...one camp thinks...especially the regulator…that the maintenance rule helped drive that change from 2.3 scrams per year to 0.7. Because....non safety stuff that could cause the plant to trip...the maintenance rule helped to develop criteria...put more focus on the maintenance of those components and scram rates went down a lot.[46]

Furthermore, in addition to the expected increased reliability and availability of plants due to a decrease in SCRAM rates, it also became apparent that fewer SCRAMS was just plain good for the life of the plants, as a plant operator explains:

The other thing that's a benefit from the maintenance rule and improved performance is that many of the systems were designed for so many startups, shutdowns, so many cycles, as you pointed out. And the fact that they're not experiencing as many SCRAMS and events as they had projected when the plants were designed...that there's fewer...there's less wear and tear on many of the components which means they have a longer life. They don't wear out as fast.[47]

Another industry engineer also quoted improved performance numbers, but in terms of overall system availability. The engineer also had an unabashed assessment of how well the industry was doing since implementation of the Maintenance Rule:

I honestly believe that maintenance rule has gotten us to the fleet average in the United States where capacity factors and availability of our nuclear fleet is 90 plus percent whereas in 1996 it was 60 percent. That's...that's a huge improvement and when you look at the number of SCRAMS, you look at all the other measures of how good the industry is doing...it's great.[48]

[46] Interviewee 002 25 May 2018, 0:39:50.
[47] Interviewee 001 13 April 2018, 1:24:25.
[48] Interviewee 005 18 June 2018, 0:54:54.

Finally, an NRC engineer summarized the effectiveness of the Maintenance Rule by strongly emphasizing how it positively improved plant risk construction and management. The engineer also not only fully endorsed the success of the rule, but also its performance based and risk informed construction:

> I think it was one of the...my personal opinion...it was one of the best rules that we've every written...it was performance based...it was risk informed. It allowed...it helped them improve performance because it allowed the facilities to think in terms of risk and be able to manage risk more effectively. So, manage the maintenance more effectively.[49]

The Maintenance Rule narratives were consistent among and across both NRC and industry engineers that I interviewed. All eight had been control room operators and some also had maintenance experience. To a person, none of the engineers felt that the Maintenance Rule was too administrative or bound its implementers in red tape. They all felt it had dramatically changed the industry for the better in terms of both safety and commercial success. From the engineers' views, it is clear that the Maintenance Rule had become a critical safety and reliability component of nuclear power plant sociotechnical systems.   While to become "super safe" requires extraordinary efforts and constant vigilance, it is evident that the people in the commercial nuclear community strongly feel that the technology of the Maintenance Rule has transformed their profession and their systems from ill-informed amateurs operating leaking machines to a professionally run and safe, if not super safe, environment.

[49] Interviewee 008 31 August 2018, 0:24:07.

A retired industry nuclear engineer summed up his feelings toward the Maintenance Rule and how it had transformed the industry when he recalled, "the bad days…we had in the nuclear industry in the 80s and 90s, but you won't find an industry in the United States that has a better safety record…and you know…the Maintenance Rule has been a significant part of that."[50]

End-of-Life: Knowing the System

Can the maintenance component, an SSC itself, of a nuclear plant indicate the approach of system end-of-life? Can this knowledge component make end-of-life legible? What would indicate end-of-life? What would the plant licensees and the owning utility companies see on their maintenance instrumentation control panel? Components of a nuclear power plant are more than hardware. Recall that in an effective maintenance program even corrective maintenance is not merely a moment of break-fix activity. It does not just engage with what failed, but *why* it failed. It traces the failure back to a root cause and that fundamental cause is often not limited to a sequence of coupled hardware interactions or failures. Failures can have a multitude of origins to include maintenance errors, inadequate or incorrect training, material failures and faulty or substandard maintenance tools. As we have seen, maintenance then feeds what it has learned from these individual corrective actions into its predictive and

[50] Interviewee 005 18 June 2018, 0:54:54.

preventive maintenance functions (programs) where they construct a view of the system's future condition. Similarly, maintenance can also construct a view of a system as it approaches its EOL or its existence within EOL.

Maintenance is also constructed to examine the condition of components to include their logistical life cycle and indicators that show the status of components within the cycle. These indicators are present throughout a system's life, but in EOL their degradation *across* a system becomes apparent. Maintenance programs are positioned and capable of making these EOL indicators legible. The indicators that are closely coupled to maintenance activities can include: time to repair, time a component is awaiting parts, ability to repair locally or external to the organization, cost-effectiveness of repair, ability to replace, availability of spares, and availability of bench-stock items (minor, use-once parts). Indicators that are more indirectly connected to maintenance include: availability of trained maintenance personnel, breadth and depth of the system's community of knowledge, availability of component vendor support, and the availability of maintenance tools and measuring instruments. Additionally, of importance, is the quality of the logistics supply "pipeline" that cycles through new, to-be-repaired and repaired components, and also the quality of the education and training "pipeline" that develops skills in new operators and maintenance personnel and maintains it throughout their careers. It is when these indicators begin to aggregate and trend toward decreasing levels of performance that the system's EOL may be approaching.

If improvements are not made to the system's technologies for an extended period then the supporting infrastructure of the system begins to atrophy. The infrastructure is comprised of all those components and activities that maintenance indicators make legible. With the infrastructure atrophied to a state where the system is no longer effectively sustainable the system has entered EOL.

Nuclear Path to End-of-Life

Until 2019, inside the Duncan Annex of Purdue University's Electrical Engineering building it was still 1962. The Duncan Annex houses the PUR-1, a pool type, 1kW, Materials Test Reactor (MTR) running on low-enriched-uranium (LEU). It was built by Lockheed Nuclear Products and first went critical on 30 August 1962.[51] Since that time nuclear engineers have come, trained on the PUR-1, and gone on to work, presumably, for decades in nuclear careers. They sat at a control console with analog gauges, edgewise panel meters, illuminated push buttons, and a few control knobs and switches. For over a half-century the reactor's fission of LEU has been controlled through that analog console with its display of physically moving meter needles and mechanical rotary dials, all hardwired into gray metal panels. In July 2019, after nearly a seven year process, PUR-1 was updated with a modern digital console with flat panel displays and computerized controls. The NRC had licensed the "first entirely digital nuclear reactor instrumentation and control (I&C) system in the USA."[52]

[51] Wiles 2019.
[52] World Nuclear News (WNN) 10 July 2019, 1.

PUR-1 is the only reactor, research or power, in the United States that has a digital control system. Purdue's reactor supervisor, Clive Townsend, described the update, “We’re going from the vacuum tubes and hand-soldered wires of the ’60s, to LEDs, Ethernet cables and advanced electronics.”[53] PUR-1 had been roused from its stasis, both regulatory and physical.

All other U.S. reactors are still being operated with analog controls that are much the same as when they first went into operation and for some power reactors that was fifty years ago. The analog systems were understood, but there are still unknowns and concerns with use of digital systems. The NRC’s Office of Nuclear Regulatory Research published several Research Information Letters (RIL) on topics to include: 1) uncertainties of software’s complex logic (NRC RIL-1001), 2) failures modes of digital systems (NRC RIL-1002), 3) hazard analysis of digital systems (RIL-1101) and also, 4) an examination of the licensing of safety critical software.[54] Furthermore, there is the ever present concern over the cyber security vulnerabilities of digital systems and the need to protect any nuclear digital systems as per 10 CFR 73.54 Protection of digital computer and communication systems and networks.[55]

While there have been varying degrees of improvements over the decades the industry is still operating the same fifty-year-old reactor designs with much of the same systems and components. Nuclear power plant technologies have not dramatically changed. After the TMI-2 accident there were forty-five new nuclear reactor units

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[53] Wiles 2019, 1.
[54] U.S. Nuclear Regulatory Commission 2015b.
[55] U.S. Nuclear Regulatory Commission 2015a.

placed into operation over the next decade, through 1989.[56] While that appears considerable, there were sixty-two power reactors canceled in that same period.[57] The effects of TMI-2 were significant. NRC historian J. Samuel Walker did not mince words in his assessment of the post TMI-2 environment, "Orders for new nuclear plants after Three Mile Island were inconceivable."[58] Nuclear power was no longer seen as "too safe to fail" by the public, or viewed as a sane investment by the electric utilities

Given the post-TMI history of commercial nuclear power in the U.S. we can view the condition of the instrumentation and control (I&C) system as a fine focus detail of the individual power plants and of the encompassing sociotechnical system of commercial nuclear power. Thinking specifically again of the analog control system we can use it as a comparative indicator to locate it in its technological environment of electronics, computers, and instrumentation technologies. The analog control system has remained in place as its originating environment has flowed around and past it. That external technological environment moved forward to 2019 while the nuclear plant analog systems remained in the early 1970s. This was not absolute since the systems were incrementally updated with, for example, changing from tubes to transistors, but it still remained an analog system while the outside world moved to digital. Inside the wire (the perimeter fence), nuclear power plants, with analog controls as just one of many component systems, function much as they had been designed to function in the 1970s with few fundamental changes. This is the case even though improved maintenance

[56] U.S. Nuclear Regulatory Commission 2019b.
[57] U.S. Nuclear Regulatory Commission 2019a.
[58] Walker 2004, 224.

knowledge technology eventually made the aging nuclear plants safer and more reliable; the overall system of nuclear power technologies was not advancing.

End-of-Life Made Legible

A nuclear power plant is not merely a technical system, but a sociotechnical system. It is more than physical artifacts. It encompasses human, organizational, and political actors and their interactions. If we know the characteristics of stasis we can detect it if we have the technology or instrumentation to do so. Further, if we know the characteristics of a system's EOL, we can detect it with the proper instrumentation. As we have discussed, the Maintenance Rule instrumented the commercial nuclear power sociotechnical system with a technical component that made legible the system beyond the immediate component failures. What are the indications of nuclear power system EOL that maintenance instrumentation could potentially detect?

Through interviews I conducted with engineers working in the nuclear industry and by attending and participating in nuclear focused conferences and workshops it became apparent to me that end-of-life indicators were legible. There were the familiar wearing out of parts and the difficulties of supply, others showed the drying up of the technical skills pipeline, economic competition from other energy sources, policy constraints, and limited national wherewithal in terms of a cohesive nuclear power strategy.

Parts and Supply

That radiation monitor...yep...it's been there for 40 years and it's doing its job...if we can get the parts we fix [it].[59] – Nuclear Engineer

As to be expected, over time, parts wear and fail. Also, over time, parts suppliers also wear and go out of business especially for component suppliers of systems that are no longer growing. This includes suppliers for not only parts such as valves and pumps, but their constitute parts such as seals, bearings, and actuating solenoids. One component could have several individual suppliers and all, or alternative sources, need to stay in business for the logistics supply system remain functional. This situation of not just aging components, but of aging parts suppliers was made quite clear to me by public comments and the interview responses I received from engineers in the industry. I am presenting several detailed and rich quotes from my interviews to show and emphasize the reality of the situation and how those involved with maintenance and repair are recognizing and pragmatically adapting to it.

At the 2017 NRC Regulatory Information Conference (RIC) in Rockville Maryland I was interested to hear a candid presentation by the CEO of the Institute of Nuclear Power Operators (INPO), retired U.S. Navy Admiral Robert F. Willard. Instead of the typical motivational speech about opportunities, innovation, and a bright future, Admiral Willard focused on a clear problem; lack of quality spare parts:

[59] Interviewee 003 08 June 2018, 0:10:58.

The nuclear industry itself and the Nuclear Regulatory Commission, Nuclear Energy Institute, all have initiatives in place to monitor for the quality of the parts that we're utilizing. And while it becomes -- it is an increasing challenge for the industry — and as the industry ages and parts become rarer for legacy plants, it will no doubt become an increasingly challenging area.[60]

Admiral Willard makes it clear that there are often no longer known good parts sitting in a warehouse ready for use. With many original equipment manufacturers out of business and their skilled people retired, some supply chain activities such as quality control, and even component engineering, have shifted somewhat downstream with the end user frequently now required to be more vigilant and active in parts availability. Admiral Willard's high-level assessment and warning was made real to me when, a year later, an engineer described how plant maintainers were working to keep things operational.

We're seeing that...we're beginning to see that...in the U.S....I mean...the plants are aging...parts...a lot of things it's hard to get replacement parts. So, we're having to either...do reverse engineering of some equipment... So...you know...that's another area where now you get to see more failures because equipment is wearing out. Or that the replacement parts you had...wasn't quite the same...and may have missed something in the design so it's not performing as you intended it to perform.[61]

[60] U.S Nuclear Regulatory Commission 2017, 30.
[61] Interviewee 007 24 August 2018, 0:51:57.

The engineer goes on to describe that maintenance personnel do their best to keep components functioning through overhauls and replacement of constituent parts, but eventually that type of maintenance reconditioning reaches a limit:

Even though the pump may be thirty or forty years old there's a lot of parts to that pump that have been replaced. The bearings have probably been replaced a couple times. Probably the impellers have been replaced....it's managing that effort to keep things running. But there does get to be a time...and it really becomes a materials issue...especially as we move toward life after sixty years old...you may need to make some wholesale replacement...of some of your pumps...things along those lines. And there may not be anyone around to replace those pumps for you.[62]

As we see above, there is concern that when components reach decades in age then there can be a problem of finding both replacement parts and companies that have the expertise to replace the components. A potential indicator of end-of-life is that this discussion is being had in the first place. With a normally operating system, even in maturity, parts would be continually improved and replaced via a functioning logistics system. At end-of-life, that logistics system may no longer exist, as a nuclear engineer explains:

We're required to have radiation monitors and I've got the same radiation monitors operating that I had installed back in the 70s….The people at the plant are lamenting the fact that they can't get parts for these things anymore and they're just kind of piecing them together and trying to keep the pumps running

[62] Interviewee 007 24 August 2018, 0:54:19.

and keep the electronics going and they're taking out cards and replacing resistors and they're taking out indicators and trying to clean them up and fix them back up.[63]

Here we see that chronic parts shortages have reduced a formal maintenance program to an informal piecemeal operation. Non-standard efforts are improvised by maintenance personnel to keep systems operating; increasing the chance of, what Sidney Dekker described as, "drifting into failure" as the practice becomes normalized.[64]

An industry nuclear engineer described why systems have not been upgraded, especially on the primary side of the plant, and also the extent of maintenance complexity incurred when some systems are upgraded and others are not. The engineer provides a candid and real life story of the workings inside a power plant:

In the nuclear industry it is much easier to do maintenance than it is to do a modification. The difference of those obviously is...you maintain what you have versus you replace [inaudible] or change what you have. There's a desire to maintain what you have to the extent that you don't have to replace it or change it because it's very expensive...paperwork wise and plant wise because of the testing and potential cable routing and other things that you have to do. So, there is always an effort to try to maintain and keep what you have. That's why we have such old systems in our plants right now. We have not upgraded the systems. You can go to a fossil plant...well, at least the ones that are still running, and you can go to the control room that looks like it was built last year, two years ago. You go into a nuclear plant and you're still looking at [laughs]...incandescent light bulbs and switches that you need two people to help turn because

[63] Interviewee 003 08 June 2018, 0:15:56.
[64] Dekker 2011, 34.

the springs are so tight [laughs]. We're just now getting to where we have agreement on how to replace some of these systems with digital systems.[65]

The regulatory change controls have not kept pace with the need to change, therefore making it more difficult, in other words, time consuming and expensive to upgrade. This requires a plant to maintain old systems with an increasingly scarce cadre of skilled technicians. In a limited sense the components can be made to work reliably and safely, but as in maintenance, they do not operationally exist outside the context of the nuclear plant system which includes maintenance programs, logistical support, policies, and skilled people in all areas. To effectively be considered safe and reliable every component must operate within and be a part of functioning technical and support systems. Of course, the expense of the bottom-line is often the bottom-line. The nuclear power plant licensees are commercial businesses manufacturing electricity. The demand for the product is in no doubt, but it must be a produced at a price that consumers are willing to pay.   To the engineers this was obvious and failure of nuclear to be cost competitive — perhaps inevitable:

The thing that's going to kill nuclear power, that's killing it right now as well as coal power and...is artificially cheap other sources of energy. Right now, fracking has driven the price of natural gas in the U.S. down to the point where...nobody can compete with it.[66]

[65] Interviewee 003 08 June 2018, 0:16:56.
[66] Interviewee 005 18 June 2018, 1:00:15.

Strategy and Policy: Thinking nuclear…or not

Turning to policy and nuclear workforce development and sustainment, a workshop brought participants from the nuclear power industry, U.S. government, academia, and the public together to discuss the current and future outlook of nuclear power.[67] There were a number of discussion points that could be EOL indicators. First, in opening conversations the participants discussed that any revival of the nuclear power industry, or the "nuclear renaissance" was exaggerated particularly after the Fukushima disaster in Japan. The nuclear industry was not growing with only two reactors under construction (Vogtle Units 3 and 4 near Waynesboro Georgia) and those being extraordinarily expensive and years behind schedule.[68] Fukushima had moved the perceived risk gauge back to a post-TMI-2 level; the trust of nuclear power technology, by the public, had been severely diminished so utilities were not making investments. Second, according to a professor of nuclear engineering, the pipeline for trained nuclear engineers and operators is barely, if at all, flowing. They said that, "We have a lack of education now…we're doing a poor job of educating engineers. We cannot support new reactors."[69] Even closer to maintenance, another participant

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[67] The workshop, Alternate Visions for Shared Nuclear Energy Policy Energy Policy: Energy, Security and Policy, was hosted by Virginia Tech in Arlington Virginia on 13 May 2019. Its objective was to examine U.S nuclear energy policy while considering that "aging domestic infrastructure, international competition from Russia, China, and others, and geopolitical instability [are creating] profound uncertainties for the U.S. nuclear industry." (REF: https://nuclear.ncr.vt.edu/news/alternative-visions-for-our-shared-nuclear-future-energy-security-policy.). Discussion among workshop panel participants (recorded in my personal notes) provided candid views of the health of the U.S. nuclear industry. Participants included those from government, industry and academia.

[68] Spector 2019.

[69] Workshop: Alternate Visions for Our Shared Nuclear Future 2019.

commented on nuclear engineering as a discipline at universities, “We are not a nuclear power plant department…we’re a nuclear engineering department.”[70] This comment focused on the skills and techniques required to operate and maintain a nuclear power plant; most workers are not nuclear engineers. They comprise a wide range of disciplines from mechanical, electrical, chemical, and materials engineers and, of course radiological health physicists and radiation safety specialists. There are also many (to our point) maintenance technicians who specialize in pumps, valves, electrical circuits, generators, turbines, cabling, testing, surveillance, and instrumentation and control systems, to name only a few. While these skills could be generic, they are typically specialized to meet the component and systems standards of the nuclear industry; an all the more difficult training and skill development pipeline to traverse — if it can be found.

At the end of the discussion, there were two blunt evaluations that indicated the health of the U.S. commercial nuclear power system. One was the assessment, made by an experienced policy maker who said that an “uneven policy environment is the biggest challenge.”[71] This included lack of recognition of nuclear’s contributions to reaching carbon goals, the need for regional spent fuel storage, and creation of nuclear policies that align with national policies that support political and international relations. The other was made by a professor of engineering who said, “There is no such thing as a nuclear industry. There is an electrical power industry.”[72] With these

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[70] Workshop: Alternate Visions for Our Shared Nuclear Future 2019.
[71] Workshop: Alternate Visions for Our Shared Nuclear Future 2019.
[72] Workshop: Alternate Visions for Our Shared Nuclear Future 2019.

assessments they are arguing that: 1) Nuclear reactors are running and producing electricity, but they are functioning in isolation, disconnected and external to an *energy* policy infrastructure. There is little or no cohesive national strategy or guidance as how the entire nuclear system (end-to-end) should be technically managed. Furthermore, nuclear power production is decoupled from international sociopolitical strategy, 2) Nuclear reactors are running and producing electricity, but they are functioning in isolation to a comprehensive *nuclear* operations and maintenance infrastructure. In the context of a diminishing system of training for operators, engineers and maintenance personnel, the nuclear system is drifting back to a fossil fuel mentality. Interest has been lost and things are edging toward a system of boiling water; regressing from the nuclear operational principle to the fossil-fuel operational principle.

In the end, for any given nuclear reactor, it may not be the failure of its components or the inability to repair or replace them that will portend the end of the system's life. It may very well be the fact that the system itself is nuclear that will ultimately spell its end due to its interaction with its own system structures. Inherent in nuclear fission is the splitting of atoms with the release of neutrons. Those neutrons interact with the metal of the reactor vessel and its cooling systems and, over the decades, cause embrittlement of the metal structures. Embrittlement can weaken the vessel and cooling system to a point where fracturing is a true hazard. Therefore, as one of the nuclear engineers told me, "You will get to a point where it's just accumulated too much damage and you're not going to be able to run the plant anymore."[73] That of course, is the ultimate maintenance indicator of end-of-life.

End-of-Life in Practice

Using maintenance program methods, as a conceptual framework for analysis, it appears to be possible to readily identify conditions that could indicate a system's end-of-life. With structured, formal, inspection procedures and a maintenance informed eye we can examine the close-in conditions and performance of system components. We can also see the condition of the systems that manufacture components and the effectiveness of the systems that manage and supply those components. The evolving and changing efforts of maintenance personnel to include their training, availability, and effectiveness is also visible. Furthermore, using the maintenance thinking of root-cause analysis we can expand our examination outward and upstream. Locating ourselves outside the immediate system we can make legible the condition of the system's economic environment and also, as applicable, the structure and conditions of industry and governmental policies and strategies that interact with and influence the system's performance. Finally, if we use our maintenance ear and pay close attention to the language used, either explicitly or implicitly, to describe system conditions such as, "We're just trying to keep things running," we can gain a less filtered and more candid view of the system and its health. We see that maintenance is more encompassing

[73] Interviewee 007 24 August 2018, 0:58:55.

than the corrective and the preventive. With this mind I have expanded the definition of maintenance. Based upon my own professional maintenance experience and my thinking on system end-of-life I define maintenance as:

Those activities, organizational structures, and thinking, that sustain a system's or component's immediate functionality, its future functionality, and its future stable existence.

As I have examined in detailed, maintaining immediate functionality is accomplished by maintainers through reactive corrective maintenance (repair) and is the exception in an effective maintenance program; systems and components should not be run to failure. Future functionality is maintained with predictive maintenance through system and component monitoring and analysis. This creates knowledge for the construction of preventive maintenance programs. Additionally, a system's and a component's future stable existence (their healthy life) is sustained by a multitude of contributing upstream activities, as I have introduced above. What might these coupled supporting activities look like conceptually and in relation to end-of-life indicators? To make the concept somewhat tangible, and linked to our nuclear power plant use case, let us begin by picturing the operating control room of that nuclear plant with its many control panels and hundreds of dials, gauges, meters and switches.

Envision, adjacent to that operational control room, perhaps separated by a glass paned wall, an End-Of-Life (EOL) Maintenance Monitoring Room. Now, imagine a tremendously large wall with rows and rows of illuminated indicators from floor to ceiling. Much like many of the 1970s era analog indicators found in American reactor control rooms, the maintenance indicators are round dial gauges. Each instrument has a single, clock-hand like pointer, that can move through a color coded, semi-circle band in the upper portion of the dial. From left to right, the indicator band is colored red, yellow and green. Now, suspend disbelief for a few moments, and imagine there is an indicator for every system, structure and component in the plant that requires maintenance; thousands of EOL dial indicators stretching off to a vanishing point. If an indicator's pointer is in the green the system or comp is not in EOL. If the pointer is in the yellow the system/component is approaching EOL and if the pointer is in the red the system/component is in EOL.[74]

Figure 1: System/Component End-of-Life (EOL) Indicator

Simple, and obviously simplified, but useful to convey my thinking of the granular legibility that maintenance activities can provide if recognized and assessed. What feeds the EOL Indicator to make EOL condition visible and understandable?

The function of an indicator is to make legible, using upstream maintenance information, the inclusive health of a system/component not only at its functional endpoint as a physical artifact, but through the length of the mechanisms that sustain

[74] In their Reactor Oversight Process (ROP) the NRC uses a similar color coding method to indicate the licensee's ability to maintain acceptable plant safety and security performance. This is described in the NRC Inspection Manual, Chapter 0608 - Performance Indicator Program (U.S Nuclear Regulatory Commission 2009).

the system/component's operational existence. A system/component arrives into existence through trains of mechanisms to include concept, design, engineering, prototyping, testing, and manufacturing. Furthermore, important to this discussion, the system/component is sustained, during its working life (its future stable existence), through a closely coupled and complex chain of maintenance mechanisms. The system/component does not live and is not maintained as a standalone artifact. To illustrate, I have borrowed a graphic representation from a quality management tool, the cause and effect Ishikawa diagram.[75]

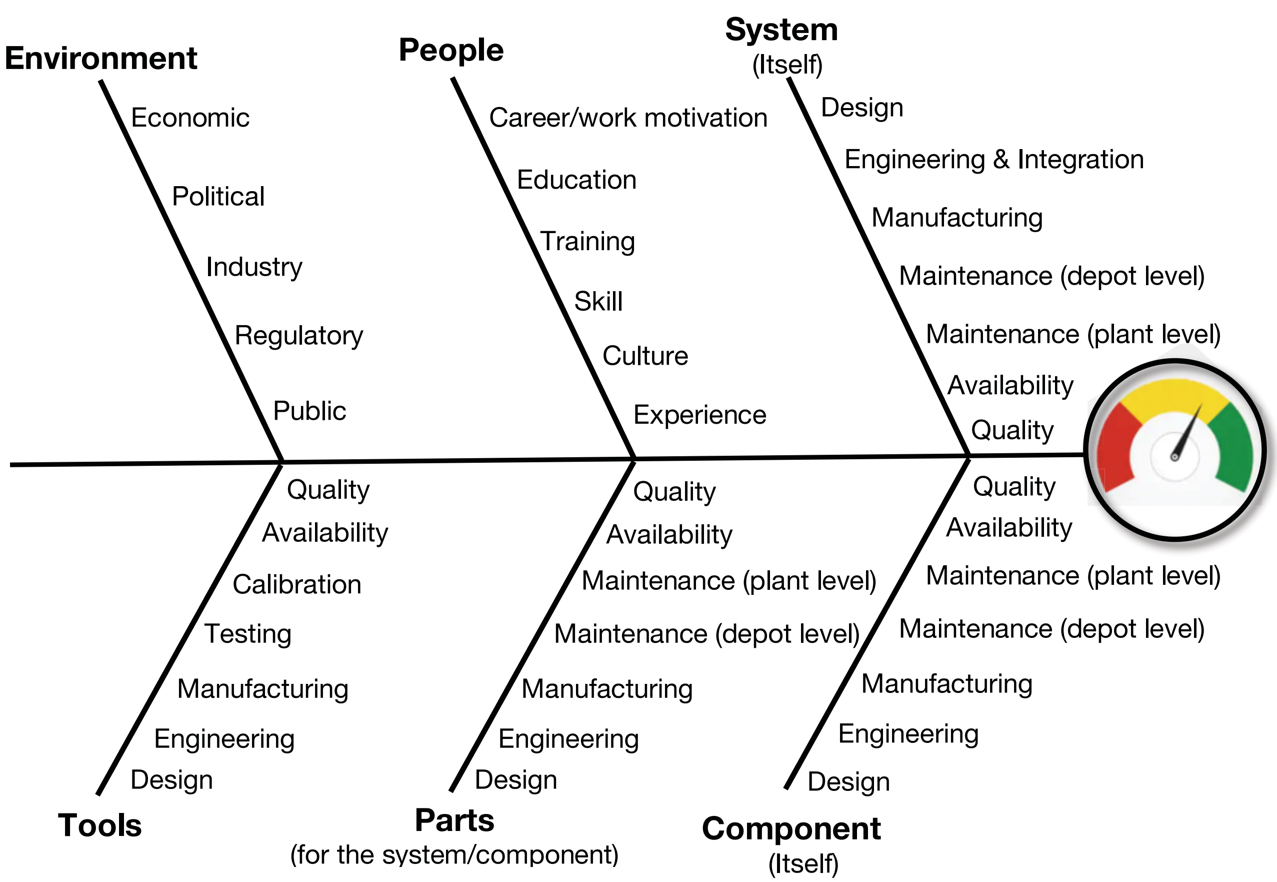

Figure 2: Maintenance Knowledge Sources w/ System/Component EOL Indicator

[75] Ishikawa 1976.

The Ishikawa, or fishbone diagram, is typically used to provide a graphical view of potential categorized causes (the fishbone) that result in a failure event shown as the head of the diagram. Similarly, I am using the Ishikawa model (see the *Maintenance Knowledge Sources and System/Component EOL Indicator* diagram) to show upstream activities or events, made legible through maintenance, that can cause the EOL indicator to register the health of a system/component or, if aggregated, the overall EOL status of the entire large-technological-system. The diagram is not all inclusive, but it represents what I have discovered in my research discussions with the nuclear industry, government, the academic community, and what my personal experience working in maintenance organizations has made legible to me.

The causes displayed on the fishbone are the sustainment causes required to maintain the functional existence of a system/component and, if extended, the overall functional existence of entire system. These causes (activities) that are functioning behind, or upstream, from a system/component are often not legible (or even visible) for the individual system/component. I would also argue that they are rarely (ever?) formally aggregated and synthesized into an indication of overall system EOL. That aggregation/synthesis gap is what I am proposing that maintenance knowledge can contribute to filling.

What I show in the diagram are system/component cause and EOL status-event chains that may have varying degrees of legibility. The system and component chains are the most likely to be recognized because they describe the typically well-known development, engineering, manufacturing, supply chain, and direct maintenance activities. The parts chain is somewhat less known unless you are immersed in the maintenance environment. To illustrate, it is not unusual to be asked, “Why do we have a shortage of spare parts?” The answer could often be, “We don’t have spare parts to fix the spare parts.” In my experience the top level “spare part” is called the “next-higher-assembly” and it generally had to be sent out (up the repair chain), in its entirety, for depot level maintenance. Depot would obviously need spare parts on hand to affect the repair. Availability of the spare parts (and skilled maintenance personnel) would determine how quickly the next-higher-assembly could be returned to the field; that determines system availability. With a maintenance informed look, we see that parts for systems and components are also constructed and constrained by their own less legible chains of development, engineering, manufacturing, supply chain and maintenance activities.

Closely coupled with maintaining systems, components and their constituent parts are tools. These are the mechanical and electronic devices and their supporting technical manuals, used to remove, install, replace, test, adjust, configure, disassemble, and assemble the systems, components and parts. The tools themselves are systems (simple and complex) that come into existence through design, engineering, and manufacturing, and also require their own predictive, preventive and sustaining maintenance by trained and skilled personnel. Recognition of maintenance tools as critical components of systems is not necessarily readily legible. I have personally seen it as generally only visible to maintenance support personnel internal to maintenance organizations themselves. Even maintenance personnel often simply expect tools to be available and serviceable without significant regard to the upstream activities that put the tool on their bench or in their hand. A maintenance program can (I have seen it) track tool maintenance and readily identify shortfalls (maintenance-built knowledge) and their impact on system and component serviceability.

Next, what of the most complex component of the system, the people? Here we can see both a supply chain and a skill chain. First, far upstream, what are the factors that motivate a person to pursue the education and training toward a discipline that sustains a large-technological-system? Besides personal interest there must be some indication to the person that there is a future to their chosen pursuit. Is there a demand for a specific maintenance skill? Are there educational and training programs that prepare personnel for the technical profession? Are the providers of these programs, such as universities and technical schools, also motivated and see a future? Looking further downstream, do the system/component designers, manufacturing engineers, and maintenance programs face shortages of qualified candidates due to attrition and retirements? Can they retain skilled engineers? If they have difficulty keeping experienced personnel is this evident in supply shortages, increased times to restore service, and overall frequency of maintenance errors? All of these types of information can be maintenance program produced knowledge.

Finally, environmental contexts decidedly play a role with maintenance and in the life of systems/components. The economic viability of maintaining a system is always a concern especially if it is privately owned and operated such as a commercial nuclear power plant. That becomes This dissertation has focused extensively on the government regulatory and the industry maintenance program environments. We have seen how the maintenance rule infused maintenance thinking within the commercial nuclear power system. The system now runs with maintenance knowledge production and has the ability to make legible indications of system end-of-life.

This exemplifies and extends the concept of running with maintenance by also running down the system/component supporting maintenance chains. Maintenance is creating knowledge and legibility of the physical artifact's requisite supporting mechanisms; what is needed to sustain (to maintain) the artifact's life. Maintenance is traversing the length of the chain and not fixated, as we have similarly examined, on simply correcting a failure with a physical system/component. The EOL system is not only running the full length of maintenance but, is also running with its breadth that includes those activities feeding into the component's sustainment. The health of each activity contributes to the overall health of a specific component or system. It is the combination of the workings of these maintenance activities that power the EOL gauge and position its pointer. Each pointer indicates the evaluated legibility of component EOL and, if all the indicators are combined and viewed as a high-resolution picture, it can make legible the EOL condition of the entire system; in our case, the evaluated life condition of a nuclear power system.

Returning to our imagined EOL Maintenance Monitoring Room what would we see in the year 2019 if we scanned the gauges? The gauge indicating economic health would be in the red. The cost effectiveness of commercial nuclear power is not remaining competitive with fossil fuel plants, especially those running on now cheap natural gas obtained from hydraulic fracture drilling techniques in the United States.[76] Surprisingly, the combined operating, maintenance, and fuel costs of nuclear power plants is about 50% less than that of fossil plants.[77] Paradoxically, this is primarily due the substantially cheaper cost of nuclear fuel compared to fossil fuel; less than a third the cost as of 2018.[78] What is it that drives up the nuclear utilities' overall cost to put electricity on the U.S. power grid? The electric power companies are on the hook to repay the tremendous capital investment costs of building nuclear power plants. They were built to strict regulatory and technical safety standards and therefore often required unique technical skills. They were also constructed to non-standardized designs by many different vendors thus making each construction unique and expensive.[79] It also typically takes a decade or more to build a plant.[80] These are some of the upstream reasons for the high downstream electricity costs from a fleet of reactors that went operational from 1969 (Nine Mile Point, Unit 1) to 2016 (Watts Bar, Unit 2).[81]

There are two reactors currently under construction in the United States; Vogtle Units 3 and 4 near Waynesboro Georgia and like the previous reactor designs they are unique. They are the first Westinghouse AP1000 reactor units to be built in the U.S. so there is little current experience in building the units and there are high manufacturing costs for the plant's systems and components due to extremely limited production runs.

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[76] U.S. Energy Information Administration 2016.
[77] U.S. Energy Information Administration 2019a.
[78] U.S. Energy Information Administration 2019a.
[79] Iurshina 2019.
[80] Rolph 1979.
[81] U.S. Nuclear Regulatory Commission 2019b. Construction of Watts Bar, Unit 2 was stopped in 1985, while work on Unit 1 continued with it going online in 1996 -- the last U.S. reactor entering service in the 20th century. In 2007, the operator of Watts Bar, Tennessee Valley Authority, restarted the process to complete Unit 2 and brought it online in 2016 (U.S. Nuclear Regulatory Commission 2016).

The Vogtle project cost had risen from $14 billion to $23 billion and a similar project in South Carolina (also for two AP1000 reactors) was terminated in 2017 after similar cost overruns that bankrupted Westinghouse.[82] As of 2018, the levelized (the combined operating and capital costs) electricity costs for nuclear power ranged from $112 to $189 per megawatt hour, while for natural gas plants it was $41 to $74 per megawatt hour.[83] The cost of competing with natural gas has moved several nuclear plants' EOL indicators firmly into the red. On 20 September 2019, Exelon corporation permanently shut down Three Mile Island Unit 1. Without state government subsidies it could no longer cost effectively produce electricity.[84]

We can also see EOL gauges making legible the supply and skill chain gaps. A gauge reading in the red is tied to the forty-year-old radiation monitors previously described. Its indicator is driven by the inability of maintainers to get parts for the monitors and also how they resort to "piecing them together."[85] Knowing that the maintainers can no longer rely upon normal maintenance supply chain activities, for spare parts, is a key piece of legible maintenance knowledge that moves the EOL indicator. Additionally, there are indicators for the systems themselves as one of the industry engineers pointed out during an interview:

Electronic and control systems…I mean…these control systems are thirty years old…and you know…who makes them anymore?[86]

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[82] Iurshina 2019.
[83] Lazard 2018.
[84] Exelon 2019.
[85] Interviewee 003 08 June 2018, 0:15:56.
[86] Interviewee 007 24 August 2018, 0:51:57.

Also, who makes the technical personnel anymore? As we saw with the discussions in the Alternate Visions workshop, the education and training pipeline for nuclear skills is no longer robust and producing a comfortable and sustaining flow of trained personnel.[87] Furthermore, I would add my own personal knowledge input to the sustainable skills EOL indicator by providing my observation of the attendees at the NRC Regulatory Information Conferences over the last several years. Seeing several thousand conferences participants each year I can describe them as being mostly middle aged, graying, men. I would also guess that their average age is most likely around 45 to 50 years old. I see the same faces every year and my gut feel is that "new blood" is not being infused into the commercial nuclear environment either with industry or the government. Finally, another "gut feel" input to the EOL indicator for the overall commercial nuclear system, is a rather resigned comment I received from a university professor at the Alternate Visions workshop during a personal conversation:

Nuclear is on life support…and if there's another accident…that's the end.[88]

I agree with the professor. For the entire commercial nuclear power system, the accident is the ultimate binary EOL indicator without a variable range. The system remains either accident free or a second accident occurs and the gauge flips from green to red. A nuclear accident would immediately end the life of the commercial nuclear industry which it nearly did after the TMI-2 accident in 1979. Most EOL indicators do

[87] Workshop: Alternate Visions for Our Shared Nuclear Future 2019.
[88] Workshop: Alternate Visions for Our Shared Nuclear Future 2019.

move within a range and, generally, any one single failure should not portend the failure of an entire system unless, of course, it is the EOL indicator for a critical, non-repairable structure such as the reactor vessel or its concrete support foundation. As I envision EOL maintenance indicators they must be evaluated as a systemic whole. Some carry more weight, or influence, than others at any given time. Risks are constructed and assigned, and reconstructed and reassigned, as the system operates, and maintenance activities create knowledge that is fed back into the functioning of the system to include EOL monitoring. For any system, there can become a time when significant numbers of EOL indicators are in the red or consistently hovering in the yellow. The system may be producing its service or product, but maintenance activities make legible that the system can no longer sustain a stable existence; it is on life support.

From my historical research, one-on-one interviews, actively engaging (with public and private questions) at NRC Regulatory Information Conferences, and by gaining personal insight from government regulators, industry engineers, and academic experts, I believe the U.S. commercial nuclear power industry is in End-Of-Life. Its thirty to fifty-year-old machines are functioning through the sustainment efforts of an extremely professional and skilled, but aging (and retiring), cadre of industry engineers and government regulators. The chains of supporting maintenance activities are gradually weakening along their lengths and eventually critical systems and components will have EOL indictors in the red without means to roll them back. My assessment is that to maintain the stable existence of the commercial nuclear industry in the United States it will require new reactor and plant designs that are economical viable, functionally safer, easier to maintain and to operate and, above all, maintained by supportive public, political and industrial environments.

Technological System Life

The increasingly legible and more candid views of a system's life condition originate from clarifying maintenance program produced knowledge. In a system running with maintenance, maintenance activities construct localized and detailed information about the system as the system is operating. This informational feedback is both current and, as I have argued, future predictive and evaluative. It makes legible what can potentially happen with the system and allow assessment as to its future condition and, for my conceptual framework, its end-of-life position. Where does it fit?

As we recall, Hughes described sociotechnical systems as following historical patterns. Patterns of evolution, expansion and contraction that include "invention, development, innovation…growth…and consolidation."[89] He said these phases are "discernable because of one or several…activities predominating during the sequence of phases."[90] Hughes gave self-explanatory examples of those respective activities being performed by inventors, developmental entrepreneurs and financiers associated with the phases. The phases are characterized by whoever is primarily performing the work at the time. Hughes further observed that the phases were "not simply sequential: they overlap and backtrack."[91] With that conceptual flexibility in mind we can also

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[89] Hughes 1987, 56-57.
[90] Hughes 1987, 57.
[91] Hughes 1987, 56.

reasonably say that maintenance is always present in a system's life, even if it may not always be fully effective. As a continuous system life-cycle thread I would not designate a distinct maintenance phase for Hughes' system pattern. But, applying his thinking for identifying and naming a phase, I will ask: When is maintenance most evident? With my concept of maintenance as a knowledge producing system component, I will argue that it is most active during a system's end-of-life. Not only is it often engaged with the repair of aging systems and components it is also, as I have described in this summary, producing much end-of-life indicating knowledge. I would say that the maintenance program control and enunciator panels of a system in end-of-life are active and illuminated. They are informing system operators and government regulators, at all levels, so they can make knowledgeable decisions concerning the life-cycle operation and regulation of the system.

Conclusion

What did I learn as I examined U.S. nuclear power system maintenance as it journeyed from a few theory confirming fissioning atoms to a fully integrated technological component of commercial nuclear power plants? Its journey proved to be an interesting story with chapters that played on the Cold War stage, survived a nuclear accident, displayed joint government and industry actions, redefined and reconstructed nuclear system maintenance and, finally, provided insight that allowed me to construct a conceptual approach toward making legible technological system end-of-life.

First, as I began looking at nuclear power plant life and the maintenance of that life, I automatically went to the gates (figurately speaking) of the first commercial power plants, designed during the Cold War of the 1950s, and peered inside the wire. How were they being maintained? I eventually discovered that they *were not* being maintained, at least in the way that I understood from my experience maintaining another large and hazardous technological system, military aircraft weapons systems. *That* was an extraordinary discovery and one that I often tell people when I talk of my research. Both those with and without maintenance experience are incredulous that a *nuclear* power plant would not be maintained, “That just wouldn’t be done, right?” I suspect both groups would be, at least vaguely, envisioning Three Mile Island, Chernobyl, and even Fukushima whether or not maintenance was involved with a particular accident. We have seen that effective maintenance is a critical systems technology and especially critical for the safety of nuclear systems.

One of the aircraft I worked as a United States Air Force maintenance person, the Convair F-106 Delta Dart fighter interceptor, was a contemporary of the first nuclear plants. In contrast to power plants such as Dresden in 1959, the F-106 weapons system *was* maintained with an effective, formalized maintenance program. As I have described, the technology of formalized, programmatic maintenance was not implemented by the U.S. nuclear industry until over three decades later. My own experience with a Cold War era technological system provides some contrasting perspective with the maintenance of commercial nuclear systems because, in fact, the F-106 was also a nuclear system. It carried an air-to-air rocket with a 1.5 kiloton nuclear warhead while its ground based technological counterpart, the Dresden power plant, operated a 200-megawatt reactor.[92] Both were small compared to later developments, but each required an investment of financial resources and human knowledge for effective maintenance and safe operations.

As I have argued, international Cold War pressures, overconfidence in knowledge of nuclear technology, and substantial cost constraints, played roles in how the private electric power companies engineered their power plants and designed and implemented nuclear system maintenance. We saw that private industry did not invest sufficient time or scarce resources (The Cold War was on!) to design robust and effective maintenance technologies. When I examine my F-106 military nuclear

[92] Federation of American Scientists 1999; Rolph 1979.

system I see that it was also designed and implemented under Cold War pressures (Air defense of Canada and the United States from Soviet bomber attack!), and with confidence in nuclear warhead safety.[93] It is the cost constraint that can distinguish the publicly funded military aircraft system from the privately funded commercial power plant. The Cold War military budget for a government owned, operated and maintained system was arguably unlimited with defense of the country as its delivered service to the American taxpayers. The Air Force and Convair could afford to invest heavily in maintenance technologies as they had been since World War II.[94] In contrast, Commonwealth Edison Company, the owner of the Dresden nuclear power plant, did not have access to the nation's taxpayer's dollars, but had to rely on its paying electricity customers. For all of the commercial nuclear operators, development of maintenance programs, especially in light of their confidence in nuclear system design and engineering, was something where they invested little. For over three decades U.S. nuclear power plants operated by in large without effective maintenance technology; maintenance remained reactive rather than programmatic. To the operators and the regulators, the system was apparently working as per thinking and expectations constructed in the environment of 1950s America.

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[93] Like the industry's confidence that nuclear plants were too safe to fail, the confidence in the F-106's nuclear rocket's warhead may have also been misplaced. The documentary film, Always/Never, by Sandia National Laboratories, seems to indicate the early W25 warhead in the rocket may have been unsafe (Sandia National Laboratories 2015).

[94] I believe the military (in this case the aviation community) had an established technical culture that included development of maintenance programs as a standard practice. I found in my father's (Private First Class Orval K. Miller, Army Air Forces) World War II technical manual for the Consolidated Aircraft Corporation's B-24D bomber a power plant Periodic Inspection Form for a 50-75 hour check (Consolidated Aircraft Corporation Flight and Service Department 1943). That is a firm example, in 1943, of a maintenance program that includes predictive and preventive maintenance. Interestingly, Consolidated Aircraft Corporation later became the Convair company, the maker of the F-106.

I showed that when the two-decade old commercial power reactor design failed at Three Mile Island Unit 2 the subsequent accident investigations and reports did not provide an adequate focus on maintenance deficiencies. The investigators, both technical and regulatory, concentrated upon failures of operations, training, and NRC policies. Their analysis was weighted heavily toward what the control room operators were doing; how they controlled the plant and how they understood how the plant was and was not functioning and responding to their commands. Each investigation's root-cause analysis placed emphasis on the TMI-2 operator's misunderstanding and misconfiguration of the malfunctioning plant and the failures of specific, physical plant components. I argue that this is not surprising since control room operations are highly visible. In fact, images of the TMI-2 control room literally appeared in the public's living rooms on television, newspapers and magazines and President Jimmy and First Lady Rosslyn Carter were seen walking through the control room. This obvious and candid visibility into the workings of a nuclear power plant (or other large technological system) shows to others where people interact with the system. Even if not in the context of a publicized system failure, operations is what is legible to many people even to those working locally to the system. In contrast, although always portrayed as closely coupled with the words "operations and maintenance," maintenance generally has limited visibility and its system interactions are not often recognized. As I discovered, in the case of the TMI-2 accident, the criticality of maintenance to a system's safety and reliability is not necessarily legible to those making regulatory and technical decisions.

Ironically, I found that while the TMI-2 investigations did not focus on the root cause of maintenance failures they did recognize that a specific failed maintenance activity was the initiating event of the accident. Here is where I argued that the TMI-2 accident was the *recognition event* of the critical importance of maintenance, but it was not the *initiating event* for development of a maintenance program that would eventually be mandated and implemented by the Maintenance Rule. The technical fuel was available, but the regulatory ignition source had yet to be lit. It was an NRC annual policy and planning document that started the fire (even if, as we have seen, it was smoldering) that, over a dozen years later, was fully implemented as the Maintenance Rule.

Traveling the path to implementation I documented how the NRC and the nuclear industry jointly developed the methods of Maintenance Rule implementation. Here was a case where implementation of a performance-based regulation was shaped by the regulator and the licensee. They mutually tuned implementation processes and standards so the licenses would know how to perform for the regulator, to ensure compliance, and the regulator would know that what they were seeing the licensee perform would be effective in meeting Maintenance Rule criteria. I assessed it as a balanced and practical approach that allowed the licensee to locally construct effective maintenance practices without the inflexible constraints of prescribed (and locally removed) regulation. These licensee, locally constructed maintenance processes and methods together with NRC Maintenance Rule inspection procedures were knowledge producing technologies that became fundamental to knowing and the condition of nuclear power plants and their functioning life.

I presented maintenance as a knowledge producing component, a technological component, of nuclear plants. I argued that the predictive and preventive maintenance technologies, framed by the Maintenance Rule, are producers of *leading-knowledge* of plant conditions. In contrast, nuclear plant operators have current or post-knowledge of plant conditions. They see a green indicator showing a present functional condition and a red indicator showing a just failed or non-functional condition. At best they would see a degrading condition, but even that is after the fact. I framed predictive/preventive maintenance as a technological indicator that was looking ahead to *when* a component or system is likely to fail. This is what I termed *running with maintenance*, within a system, rather than running to maintenance or running to failure and, if lucky, minor corrective action or, if dramatically unlucky, a catastrophic accident.

I further presented my own definition of maintenance that extended its typical definition beyond corrective action, and close-in predictive and preventive knowledge producing activities. I proposed that it include an enhanced knowledge producing function. A technology that monitors upstream maintenance activities that are required to sustain a system's or component's functional life. What that definition of maintenance in mind I then proposed a conceptual model of an instrument that would indicate system/component end-of-life and, if aggregated and evaluated, the end-of-life of an overall technological system. I believe this conceptual method can be a practical method with current techniques of data collection and trending analysis. It can make legible system end-of-life if there is an idea of what to examine. With end-of-life visible and understood it can conceptually extend system theory to enable better decisions regarding functional operations, safety, risk acceptance, and continued investment and expenditure of resources. Is it time to shut down and retire a system?

Finally, from my research, information gathering, and thinking about that information through the conceptual framework of my EOL model, I concluded that the current American commercial nuclear power industry is at end-of-life. It does not appear to be sustainable with its current static, instantiation of aging power plants and weakening upstream supporting maintenance mechanisms. Even with that assessment I will say that the current nuclear system is being heroically operated and maintained by a group of skilled and professional people. I was continually impressed by the expertise, dedication and professionalism of the nuclear operators, engineers, scientists, policy makers and academics I met and talked with throughout the industry and the government. Their technical and professional spirit is not at end-of-life.

Appendix A – The Maintenance Rule[95]

31324 Federal Register / Vol. 56, No. 132 / Wednesday, July 10, 1991 / Rules and Regulations

PART 50—DOMESTIC LICENSING OF PRODUCTION AND UTILIZATION FACILITIES

1. The authority citation for part 50 is revised to read as follows:

Authority: Secs. 102, 103, 104, 105, 161, 182, 183, 186, 189, 68 Stat. 936, 937, 938, 948, 953, 954, 955, 956, as amended, sec. 234, 83 Stat. 1244, as amended (42 U.S.C. 2132, 2133, 2134, 2135, 2201, 2232, 2233, 2236, 2239, 2282); secs. 201, as amended, 202, 206, 88 Stat. 1242, as amended, 1244, 1246 (42 U.S.C. 5841, 5842, 5846).

Section 50.7 also issued under Pub. L. 95–601, sec. 10, 92 Stat. 2951 (42 U.S.C. 5851). Section 50.10 also issued under secs. 101, 185, 68 Stat. 936 , 955, as amended (42 U.S.C. 2131, 2235), sec. 102, Pub. L. 91–190, 83 Stat. 853 (42 U.S.C. 4332). Sections 50.13, 50.54(dd), and 50.103 also issued under sec. 108, 68 Stat. 939, as amended (42 U.S.C. 2138). Sections 50.23, 50.35, 50.55, and 50.56 also issued under sec. 185, 68 Stat. 955 (42 U.S.C. 2235). Sections 50.33a, 50.55a, and Appendix Q also issued under sec. 102, Pub. L. 91–190, 83 Stat. 853 (42 U.S.C. 4332). Sections 50.34 and 50.54 also issued under sec. 204, 88 Stat. 1245 (42 U.S.C. 5844). Sections 50.58, 50.91, and 50.92 also issued under Pub. L. 97–415, 96 Stat. 2073 (42 U.S.C. 2239). Section 50.78 also issued under sec. 122, 68 Stat. 939 (42 U.S.C. 2152). Sections 50.80–50.81 also issued under sec. 184, 68 Stat. 954, as amended (42 U.S.C. 2234). Appendix F also issued under sec. 187, 68 Stat. 955 (42 U.S.C. 2237).

For the purposes of sec. 223, 68 Stat. 958, as amended (42 U.S.C. 2273); §§ 50.46 (a) and (b), 50.54(c) are issued under sec. 161b, 68 Stat. 948, as amended (42 U.S.C. 2201(b)); §§ 50.7(a), 50.10 (a)–(c), 50.34 (a) and (e), 50.44 (a)–(c), 50.46 (a) and (b), 50.47(b), 50.48 (a), (c), (d), and (e), 50.49(a), 50.54(a) (i), (i)(1), (1)–(n), (p), (q), (t), (v), and (y), 50.55(f), 50.55a (a), (c)–(e), (g), and (h), 50.59(c), 50.60(a), 50.62(b), 50.64(b), 50.65, and 50.80 (a) and (b) are issued under sec. 161i, 68 Stat. 949, as amended (42 U.S.C. 2201 (i)); and §§ 50.49 (d), (h), and (j), 50.54 (w), (z), (bb), (cc), and (dd), 50.55(e), 50.59(b), 50.61(b), 50.62(b), 50.70(a), 50.71 (a)–(c) and (e), 50.72(a), 50.73 (a) and (b), 50.74, 50.78, and 50.90 are issued under sec. 161(o), 68 Stat. 950, as amended (42 U.S.C. 2201(o)).

2. A new § 50.65 is added to read as follows:

§ 50.65 Requirements for monitoring the effectiveness of maintenance at nuclear power plants.

(a) (1) Each holder of an operating license under §§ 50.21(b) or 50.22 shall monitor the performance or condition of structures, systems, or components, against licensee-established goals, in a manner sufficient to provide reasonable assurance that such structures, systems, and components, as defined in paragraph (b), are capable of fulfilling their intended functions. Such goals shall be established commensurate with safety and, where practical, take into account industry-wide operating experience. When the performance or condition of a structure, system, or component does not meet established goals, appropriate corrective action shall be taken.

(2) Monitoring as specified in paragraph (a)(1) of this section is not required where it has been demonstrated that the performance or condition of a structure, system, or component is being effectively controlled through the performance of appropriate preventive maintenance, such that the structure, system, or component remains capable of performing its intended function.

(3) Performance and condition monitoring activities and associated goals and preventive maintenance activities shall be evaluated at least annually, taking into account, where practical, industry-wide operating experience. Adjustments shall be made where necessary to ensure that the objective of preventing failures of structures, systems, and components through maintenance is appropriately balanced against the objective of minimizing unavailability of structures, systems, and components due to monitoring or preventive maintenance. In performing monitoring and preventive maintenance activities, an assessment of the total plant equipment that is out of service should be taken into account to determine the overall effect on performance of safety functions.

(b) The scope of the monitoring program specified in paragraph (a)(1) of this section shall include safety related and nonsafety related structures, systems, and components, as follows:

(1) Safety related structures, systems, or components that are relied upon to remain functional during and following design basis events to ensure the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, and the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposure comparable to the 10 CFR part 100 guidelines.

(2) Nonsafety related structures, systems, or components:

(i) That are relied upon to mitigate accidents or transients or are used in plant emergency operating procedures (EOPs); or

(ii) Whose failure could prevent safety-related structures, systems, and components from fulfilling their safety-related function; or

(iii) Whose failure could cause a reactor scram or actuation of a safety-related system.

(c) The requirements of this section shall be implemented by each licensee no later than July 10, 1996.

Dated at Rockville, Maryland, this 28th day of June, 1991.

For the Nuclear Regulatory Commission.

Samuel J. Chilk,

Secretary of the Commission.

[FR Doc. 91–16322 Filed 7–9–91; 8:45 am]

BILLING CODE 7590-01-M

DEPARTMENT OF TRANSPORTATION

Federal Aviation Administration

14 CFR Part 39

[Docket No. 90–CE–73–AD; Amdt. 39–7054; AD 91–14–13]

Airworthiness Directives; Beech 33, 35, and 36 Series Airplanes

AGENCY: Federal Aviation Administration (FAA), DOT.

ACTION: Final rule.

SUMMARY: This amendment adopts a new airworthiness directive (AD) that is applicable to certain Beech 33, 35, and 36 series airplanes. This action requires initial and repetitive inspections for cracks in the wing front carry-through frame structure and repair or reinforcement if found cracked. Reports indicate that several of the affected airplanes have developed cracks in this structure. The actions specified by this AD are intended to prevent structural damage to the wing that could progress to the point of failure.

DATES: Effective August 12, 1991. The incorporation by reference of certain publications listed in the regulations is approved by the Director of the Federal Register as of August 12, 1991.

ADDRESSES: Beech Service Bulletin No. 2360, dated November 1990, that is discussed in this AD may be obtained from the Beech Aircraft Corporation, P.O. Box 85, Wichita, Kansas 67201–0085. This information may also be examined at the FAA, Central Region, Office of the Assistant Chief Counsel, room 1558, 601 E. 12th Street, Kansas City, Missouri 64106.

FOR FURTHER INFORMATION CONTACT: Mr. Larry Engler, Aerospace Engineer, Wichita Aircraft Certification Office, 1801 Airport Road, room 100, Mid-Continent Airport, Wichita, Kansas 67209; Telephone (316) 946–4409.

SUPPLEMENTARY INFORMATION: A proposal to amend part 39 of the Federal Aviation Regulations to include an AD that is applicable to certain Beech 33, 35, and 36 series airplanes was published in

[95] U.S. Nuclear Regulatory Commission 1991.

Appendix B – NRC Regulatory Guide[96]

U.S. NUCLEAR REGULATORY COMMISSION June 1993

REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RESEARCH

REGULATORY GUIDE 1.160
(Draft was DG-1020)

MONITORING THE EFFECTIVENESS OF MAINTENANCE AT NUCLEAR POWER PLANTS

A. INTRODUCTION

The NRC published the maintenance rule on July 10, 1991, as Section 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," of 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities." The Commission's determination that a maintenance rule was needed arose from the conclusion that proper maintenance is essential to plant safety. As discussed in the regulatory analysis for this rule,[1] there is a clear link between effective maintenance and safety as it relates to such factors as the number of transients and challenges to safety systems and the associated need for operability, availability, and reliability of safety equipment. In addition, good maintenance is also important in providing assurance that failures of other than safety-related structures, systems, and components (SSCs) that could initiate or adversely affect a transient or accident are minimized. Minimizing challenges to safety systems is consistent with the Commission's defense-in-depth philosophy. Maintenance is also important to ensure that design assumptions and margins in the original design basis are maintained and are not unacceptably degraded. Therefore, nuclear power plant maintenance is clearly important in protecting the public health and safety.

Paragraph (a)(1) of 10 CFR 50.65 requires that power reactor licensees monitor the performance or condition of SSCs against licensee-established goals in a manner sufficient to provide reasonable assurance that such SSCs are capable of fulfilling their intended functions. Such goals are to be established commensurate with safety and, where practical, take into account industry-wide operating experience. When the performance or condition of an SSC does not meet established goals, appropriate corrective action must be taken.

Paragraph (a)(2) of 10 CFR 50.65 states that monitoring as specified in paragraph (a)(1) is not required where it has been demonstrated that the performance or condition of an SSC is being effectively controlled through the performance of appropriate preventive maintenance, such that the SSC remains capable of performing its intended function.

Paragraph (a)(3) of 10 CFR 50.65 requires that performance and condition monitoring activities and associated goals and preventive maintenance activities must be evaluated at least annually,[2] taking into

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[1]NRC Memorandum to All Commissioners from J. Taylor on "Maintenance Rulemaking," June 27, 1991. Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555; phone (202) 634-3273; fax (202) 634-3343.

[2]As of the publication of this regulatory guide, a modification to the maintenance rule is in preparation that would change the evaluation interval to every refueling outage but not to exceed 2 years.

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[96] U.S. Nuclear Regulatory Commission 1993.

account, where practical, industry-wide operating experience. Adjustments must be made where necessary to ensure that the objective of preventing failures of SSCs through maintenance is appropriately balanced against the objective of minimizing unavailability of SSCs because of monitoring or preventive maintenance. In performing monitoring and preventive maintenance activities, an assessment of the total plant equipment that is out of service should be taken into account to determine the overall effect on performance of safety functions. Paragraph (b) of 10 CFR 50.65 states that the scope of the monitoring program specified in paragraph (a)(1) is to include safety-related and nonsafety-related SSCs, as follows:

(1) Safety-related structures, systems, or components that are relied upon to remain functional during and following design basis events to ensure the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, and the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposure comparable to the 10 CFR Part 100 guidelines.

(2) Nonsafety-related structures, systems, or components

  (i) That are relied upon to mitigate accidents or transients or are used in plant emergency operating procedures (EOPs); or

  (ii) Whose failure could prevent safety-related structures, systems, and components from fulfilling their safety-related function; or

  (iii) Whose failure could cause a reactor scram or actuation of a safety-related system.

Paragraph (c) of 10 CFR 50.65 states that the rule provisions are to be implemented by licensees no later than July 10, 1996.

Any information collection activities mentioned in this regulatory guide are contained as requirements in 10 CFR Part 50, which provides the regulatory basis for this guide. The information collection requirements in 10 CFR Part 50 have been approved by the Office of Management and Budget, Approval No. 3150-0011.

B. DISCUSSION

The objective of 10 CFR 50.65 (referred to hereafter as the maintenance rule or the rule) is to require monitoring of the overall continuing effectiveness of licensee maintenance programs to ensure that: (1) safety-related and certain nonsafety-related SSCs are capable of performing their intended functions and (2) for nonsafety-related equipment, failures will not occur that prevent the fulfillment of safety-related functions, and failures resulting in scrams and unnecessary actuations of safety-related systems are minimized.

The extent of monitoring may vary from system to system depending on the system's importance to risk. Some monitoring at the component level may be necessary; however, it is envisioned that most of the monitoring could be done at the plant, system, or train level. For example, for less risk-significant systems, indicators of system reliability (where sufficient performance data exist) and availability may be all that is necessary. For more risk-significant systems, some parameter trending, beyond that already required by NRC requirements to provide early warning of degradation, may also be necessary for critical components whose unavailability causes a system train to be unavailable or whose failure is otherwise unacceptable. Rather than monitoring the many SSCs that could cause plant scrams, the licensee may choose to establish a performance indicator for unplanned automatic scrams and, where scrams caused by equipment failures have been problematic or where such scrams are anticipated, the licensee may choose to monitor those initiators most likely to cause scrams.

It is intended that activities currently being conducted by licensees, such as technical specification surveillance testing, can satisfy monitoring requirements. Such activities could be integrated with, and provide the basis for, the requisite level of monitoring. Consistent with the underlying purposes of the rule, maximum flexibility should be offered to licensees in establishing and modifying their monitoring activities.

Licensees are encouraged to consider the use of reliability-based methods for developing the preventive maintenance programs covered under paragraph (a)(2) of the rule; however, the use of such methods is not required.

With regard to the scope of the maintenance rule, as stated in paragraph (b) of the rule, it is understood that balance of plant (BOP) SSCs may have been designed and built with normal industrial quality and may not meet the standards in Appendix B to 10 CFR Part 50. It is not the intent to require licensees to generate paperwork to document the basis for the design, fabrication, and construction of BOP equipment.

Each licensee's maintenance efforts should minimize failures in both safety-related and BOP SSCs that affect safe operation of the plant. The effectiveness of maintenance programs should be maintained for the operational life of the facility.

As noted in the Regulatory Position, there may be a need to address maintenance activities that occur in the switchyards that could directly affect plant operations. Plant management should be aware of and have the ability to control these activities.

The regulatory guidance is intended to provide flexibility for a licensee to structure its maintenance program in accordance with the safety significance of those SSCs within the scope of the rule.

The nuclear industry has developed a document that provides guidance to licensees regarding implementation of the maintenance rule. This document has been prepared by NUMARC. A verification and validation (V&V) effort was conducted by NUMARC, with NRC staff observation, to test the guidance document on several representative systems. A number of changes were made to the NUMARC guidance document based on the results of the V&V effort. The NRC staff reviewed this document and found that it provides acceptable guidance to licensees.

Certain requirements for a renewed license under 10 CFR Part 54 may be satisfied by taking credit for activities required by the maintenance rule. However, the renewal rule requires (10 CFR 54.21(a)(6)(iii)), among other provisions, that an effective program must be implemented by the facility operating procedures and reviewed by the on-site review committee. The maintenance rule does not have these requirements.

Industry and NRC-sponsored probabilistic risk analyses (PRAs) have shown the risk significance of emergency ac power sources. The station blackout rule (10 CFR 50.63) required plant-specific coping analyses to ensure that a plant could withstand a total loss of ac power for a specified duration and to determine appropriate actions to mitigate the effects of a total loss of ac power. During the station blackout reviews, most licensees (1) made a commitment to implement an emergency diesel generator (EDG) reliability program in accordance with NRC regulatory guidance but reserved the option to later adopt the outcome of Generic Issue B-56 resolution, (2) stated that they had or will implement an equivalent program, or (3) endorsed the program embodied in NUMARC 87-00, Revision 1, August 1991, "Guidelines and Technical Bases for NUMARC Initiatives Addressing Station Blackout at Light Water Reactors" (i.e., maintain the emergency diesel generator target reliability of 0.95 or 0.975). Subsequently, utilities docketed commitments to maintain their selected target reliability values. Those values could be used as a goal or as a performance criterion for emergency diesel generator reliability under the maintenance rule.

When utilities were performing their plant-specific coping analyses, they were allowed to use plant-specific data concerning unavailability due to maintenance. Therefore, emergency diesel generator unavailability due to maintenance, as assumed in a plant-specific individual plant examination (IPE) analysis, could also be used as the basis for a goal or performance criterion under the maintenance rule.

Section (a)(3) of the maintenance rule requires that adjustments be made where necessary to ensure that the objective of preventing failures of SSCs through maintenance is appropriately balanced against the objective of minimizing unavailability of SSCs due to monitoring or preventive maintenance. Therefore, plant-specific emergency diesel generator reliability and unavailability should be monitored as goals under 10 CFR 50.65(a)(1) or established as performance criteria under the plant's preventive maintenance program under 10 CFR 50.65(a)(2), taking into account the objectives of 10 CFR 50.65(a)(3).

Under 10 CFR 50.65(a)(2), the utility would establish performance criteria for both emergency diesel generator reliability and unavailability. Emergency diesel generator performance criteria for reliability would be met by the absence of a maintenance-preventable failure or the occurrence of a single maintenance-preventable failure followed by appropriate root cause determination and corrective action. Performance criteria for unavailability would be met by having fewer unavailable hours, on a rolling 1-year basis, than required by the established performance criteria.

If any performance criterion is not met, or a second emergency diesel generator maintenance-preventable failure occurs, it is expected that the licensee would establish goals and monitor subsequent emergency diesel generator performance under 10 CFR 50.65(a)(1), consistent with an appropriate balance between emergency diesel generator reliability and unavailability.

The emergency diesel generator reliability performance criteria or goals selected for implementing the intent of 10 CFR 50.63 for coping with station blackout could be monitored through the use of the triggers[3] and the monitoring methods described in Appendix D of NUMARC 87-00, Revision 1, "Guidelines and Technical Bases for NUMARC Initiatives Addressing Station Blackout at LWRs," August 1991 (except for triggers and testing for "problem diesels" as described in paragraph D.2.4.4 of NUMARC 87-00, which will be addressed separately by the NRC). An acceptable unavailability goal could be to have fewer hours unavailable (on a rolling 1-year basis) than the number of hours established as acceptable by the licensee.

C. REGULATORY POSITION

The scope of monitoring efforts under the maintenance rule, as defined in 10 CFR 50.65(b), encompasses those SSCs that directly and significantly affect

[3]The triggers are intended to indicate when emergency diesel generator performance problems exist such that additional monitoring or corrective action is necessary. It is recognized that it is not practical to demonstrate by statistical analysis that conformance to the trigger values will ensure the attainment of high reliability, with a reasonable degree of confidence, of individual EDG units.

plant operations, regardless of what organization actually performs the maintenance activities. Maintenance activities that occur in the switchyard can directly affect plant operations, and as a result electrical distribution equipment out to the first inter-tie with the off-site distribution system (i.e., equipment in the switchyard) should be considered for comparison with 10 CFR 50.65(b) for inclusion under the scope of the maintenance rule.

NUMARC 93-01, dated May 1993, "Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants,"[4] provides methods acceptable to the NRC staff for complying with the provisions of 10 CFR 50.65. NUMARC 93-01 references other documents, but NRC's endorsement of NUMARC 93-01 should not be considered as endorsement of the referenced documents.

The example in NUMARC 93-01, Section 12.2.4, which refers to optimizing emergency diesel generator reliability and availability, describes an acceptable method to establish emergency diesel generator performance criteria and/or goals and subsequently monitor emergency diesel generator performance.

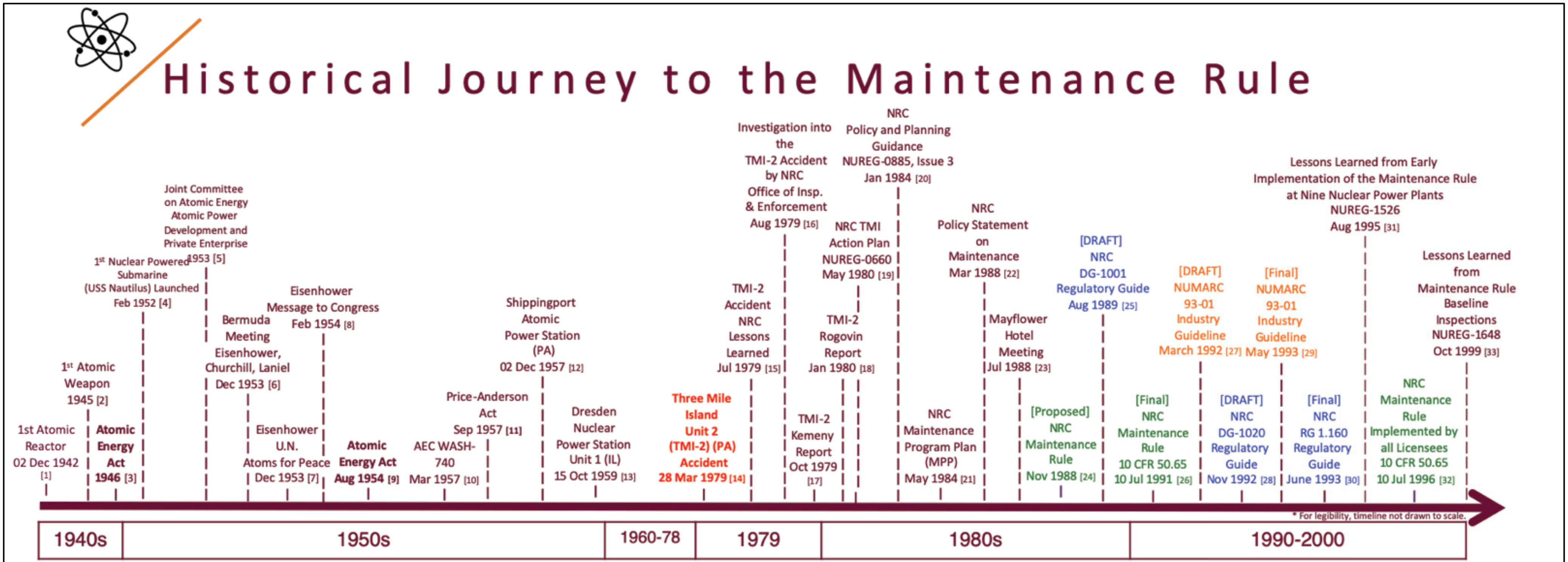
[4]Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555; phone (202) 634-3273; fax (202) 634-3343.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

Except in those cases in which the applicant or licensee proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the methods described in the guide will be used in the evaluation of submittals for construction permits and operating licenses (as appropriate) and will be used to evaluate the effectiveness of maintenance activities of licensees who are required to comply with 10 CFR 50.65. The guide will also be used to evaluate the effectiveness of emergency diesel generator maintenance activities associated with compliance with 10 CFR 50.63.

Appendix C – Maintenance Rule Historical Timeline



[1] Chicago Pile-1, first fission experimental reactor project lead by Enrico Fermi
[2] Manhattan Project – device detonated on 16 Jul 1945
[3] Established law for government civilian control of atomic weapons and energy. Created the Atomic Energy Commission (AEC). Restricted all atomic information to the U.S.
[4] Developed under leadership of U.S. Navy Admiral Hyman Rickover. Used a pressurized water reactor (PWR).
[5] Sixteen day meeting, with government and industry, to discuss how to move from a nationally controlled scientific and technological nuclear system to one that included private enterprise resources and investments.
[6] Meeting between leaders of the U.S., UK, and France to discuss how the nations should posture themselves toward the Soviet Union after the death of Stalin and how atomic information could potentially be shared.
[7] Eisenhower's address to the UN General Assembly where he proposed the creation of an international atomic energy agency and the worldwide promotion and use of atomic of energy.
[8] Eisenhower's appeal to Congress to amend the Atomic Energy Act of 1946 to allow sharing of atomic energy information. Supported "Atoms for Peace."
[9] Amended 1946 Act and allowed the U.S. to develop and share nuclear technologies, internationally, with current and potential allies.
[10] AEC study on, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants"
[11] Act to have the Federal government provide indemnification of electric utility companies in the event of catastrophic failure of nuclear reactors
[12] First demonstration power plant jointly constructed and operated by the AEC and the Duquesne Light Company. Managed by Rickover with a PWR design as used in Nautilus.
[13] First privately financed, constructed and operated nuclear power station in the U.S. (Commonwealth Edison).
[14] Most significant accident in history of U.S. nuclear power. Plants were not too safe to fail and maintenance was an initiating event.
[15] An NRC task force with the objective to quickly assess the TMI-2 accident and identify corrective actions that the NRC and nuclear power plant licenses could implement, across the reactor fleet, in the short-term.
[16] Examined the actions the TMI licensee took just before the initiating event occurred to when primary coolant flow to the reactor was restored, and how the licensee controlled radioactive release and implemented its emergency response plans.
[17] Kemeny Report: U.S. President Carter's independent investigative commission.
[18] Rogovin Report: NRC's contracted investigation (Rogovin law firm)
[19] Post TMI actions focused to improve regulation and operations of nuclear plants.
[20] NRC's normal annual policy plan that forced movement on Maint. Rule development.
[21] The first foray into maintenance program thinking by the NRC.
[22] Formalized the Commission's position that maintenance should be done.
[23] The venue where the NRC made clear to industry that nuclear power plant maintenance *would be* defined and formalized.
[24] NRC's formal engagement with the nuclear industry, via the Federal Register, to build the maintenance rule.
[25] NRC's suggested (to industry) maintenance program framework that could meet the requirements of the Maintenance Rule.
[26] Finalized and published Maintenance Rule. Initiated a five year implementation plan.
[27] Industry's draft program guideline for their planned implementation of the Maintenance Rule.
[28] NRC's response to the industry's draft guideline. An initial endorsement.
[29] Industry's final program guideline for Maintenance Rule Implementation. Informed by the NRC Regulatory Guide.
[30] NRC's final endorsement of the Industry's Guideline.
[31] Assessment of licensees who were early adopters of the MR.
[32] Mandated implementation date for industry 5 years after publication of the final Maintenance Rule in 1991.
[33] NRC inspection and verification that the licensees were effectively executing maintenance programs.

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Interviewee 002. 25 May 2018. Maintenance Rule Interview of a nuclear engineer working for an organization that advocates for the U.S. commercial nuclear power industry. Telephone interview conducted from Woodbridge, Virginia U.S.A.

Interviewee 003. 08 June 2018. Maintenance Rule Interview of a nuclear engineer working within the U.S. commercial nuclear power industry. In-person interview conducted in Washington, D.C. U.S.A.

Interviewee 004. 14 June 2018. Maintenance Rule Interview of a nuclear engineer working within the U.S. commercial nuclear power industry. Telephone interview conducted from Woodbridge, Virginia U.S.A.

Interviewee 005. 18 June 2018. Maintenance Rule Interview of a nuclear engineer working for an organization that advocates for the U.S. commercial nuclear power industry. Telephone interview conducted from Woodbridge, Virginia U.S.A.

Interviewee 006. 17 August 2018. Maintenance Rule Interview of a nuclear engineer working for the U.S. Nuclear Regulatory Commission. Telephone interview conducted from Woodbridge, Virginia U.S.A.

Interviewee 007. 24 August 2018. Maintenance Rule Interview of a nuclear engineer working within the U.S. commercial nuclear power industry. Telephone interview conducted from Woodbridge, Virginia U.S.A.

Interviewee 008. 31 August 2018. Maintenance Rule Interview of a nuclear engineer working for the U.S. Nuclear Regulatory Commission. Telephone interview conducted from Woodbridge, Virginia U.S.A.