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Social Scientists in an Adversarial Environment: The Nuclear Regulatory Commission and Organizational Factors Research

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Abstract — *This paper examines the Nuclear Regulatory Commission's (NRC's) pursuit of social science research that could inform the oversight of nuclear power plant management. Perhaps no nuclear regulator has been as supportive of research on the intersection of organizational factors and reactor safety or as cautious in applying those findings to its regulations.*

This dissonance was rooted in the NRC's long-held conviction that it should regulate power plants not people, which conflicted with its regulatory experience after the 1979 Three Mile Island accident (TMI). Intrusive oversight of a licensee's "business," it was believed, would destroy its sense of ownership for safety. TMI challenged that understanding of the NRC's role, and a series of mishaps at other plants compelled the agency to cross the line between regulation and management. The NRC's relationship with industry became highly adversarial, and the agency turned to social scientists to help establish an objective basis to judge a licensee's organizational culture. Behavioral experts joined plant oversight review teams and received generous funding to quantify the contribution of organizational factors to accident risk. Scores of scholars at national laboratories and a dozen universities contributed, but the NRC abandoned the research in the mid-1990s in the face of inconclusive research and industry resistance.

In need of a less controversial oversight program, the NRC abandoned direct assessment of plant management for a more quantitative approach that relied on plant performance indicators. When the 2002 Davis-Besse vessel head erosion event came perilously close to a significant loss-of-coolant accident, it raised questions about the appropriate role for the NRC in assessing a licensee's safety culture. The NRC revised its oversight program to incorporate qualitative insights from its earlier research while still acknowledging the line between regulation and management. The NRC learned that while there were substantial cultural and technical obstacles to integrating safety culture insights with established management and regulatory practices, it was necessary to overcome them. The agency found stability in its contentious oversight program only when it made appropriate room for safety culture expertise.

Keywords — *History of nuclear power, organizational factors, safety culture, probabilistic risk assessment, U.S. Nuclear Regulatory Commission.*

I. INTRODUCTION

For social scientists, fitting into the world of nuclear energy has been difficult. Psychologists quickly established themselves in the human factors profession during World War II in aircraft design. By the 1960s, human factors experts had a firm foothold in the defense and commercial aircraft industries, aerospace, the military, and consumer applications, but respect was harder to

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find in nuclear power, and especially, in the nuclear navy, which had inspired the U.S. civilian enterprise.

In a 1969 episode notorious in the human factors community, Admiral Hyman Rickover, the director of the office U.S. Naval Reactors, made plain his lack of respect for human factors "engineers." The father of the nuclear navy fired off a memorandum of protest after receiving a report on the Navy's plans for a comprehensive human factors program in research and engineering. He called the program "the greatest quantity of nonsense I have ever seen . . .. It is replete with obtuse jargon and sham-scientific expressions." The program would require "a vast new social 'science' bureaucracy contributing absolutely nothing to the building of ships." Before an appreciative congressional committee, Rickover elaborated with relish on his dim view of the social "sciences." "I could just imagine . . . one of these specialists advising a project engineer that . . . his fire control panel should play soft background music to ease the tension during combat." For engineers, he concluded, a human factors program was "about as useful as teaching your grandmother how to suck an egg."[1,2a]

The human factors profession won a little more respect after the 1979 Three Mile Island (TMI) accident when the U.S. Nuclear Regulatory Commission (NRC) launched a research program into the influence of human and organizational factors. Even so, the struggle for acceptance continues today in an industry dominated by engineers and nuclear navy veterans. Dr. Valerie Barnes, a psychologist, spent a career in the nuclear industry and at the NRC. Until her recent retirement, she was among a cadre of NRC social scientists that oversaw its human factors, organizational factors, and safety culture programs. She recalled her engineering colleagues did not understand that she was an industrial psychologist, not a therapist who saw patients. They dismissed her disciplinary methods and insights into human behavior and culture as "fluffy," unquantifiable, and of limited value in regulation compared to the hard quantification bent of engineering disciplines. Despite a career in the nuclear power industry and regulation, she concluded, "We spoke completely different languages."[3]

This paper details an ambitious NRC program in the early 1990s to get social scientists and engineers to speak the same language. The agency tried to translate the qualitative results of social science research on organizational factors as inputs into probabilistic risk assessments (PRAs). Using the latest social science methods and tools, the NRC aimed to develop quantitative indicators of organizational factors that, when plugged into a PRA, would flag a licensee's degrading performance and trigger regulatory action. It was a generously funded and somewhat quixotic campaign. Perhaps no nuclear regulator was as supportive of research on the nexus of organizational factors and reactor safety or as conflicted in applying those findings to its regulations.

The NRC's ambivalent quest to quantify organizational factors sprang from skepticism of the value of the social sciences in nuclear operations and an engrained belief that the agency should regulate power plants not people. Intrusive oversight of a licensee's business might destroy its sense of ownership for safety. Yet, TMI challenged these misgivings, and subsequent plant mishaps compelled the agency to cross the line between regulation and management. The NRC-industry relationship became highly adversarial, and the agency turned to social scientists to establish an objective basis to judge whether a licensee's management and organizational culture provided adequate operational safety. Experts in organizational management and behavioral sciences joined plant oversight review teams and received funding to develop indicators of the organizational contribution to accident risk. Under the direction of Brookhaven National Laboratory, scores of scholars at national laboratories, institutes, and a dozen universities contributed to the project's goal of studying in-depth licensee operational and safety cultures.

The social science researchers who stepped into plant control rooms, however, became part of the NRC's adversarial relationship with industry. They were greeted with suspicion by licensees and skepticism by regulators, especially when their research findings came to the disappointing conclusion that the risks posed by poor management attitudes and practices were not quantifiable. Their more qualitative insights and methods were useful but labor intensive and divisive. The NRC abandoned the work in the mid-1990s. Without an impartial, objective measure of organizational performance, the NRC's oversight program was mired in controversy.

In the late 1990s, the improved safety performance of its licensees and an industry-friendly climate in Congress compelled the NRC to craft a less controversial oversight program that was more performance-based and quantitative. In the new program, the agency avoided direct evaluation of unquantifiable factors such as licensee safety culture. When in 2002 the vessel head on the Davis-Besse nuclear power plant suffered severe erosion and came perilously close to a loss-of-coolant accident, questions about the NRC's appropriate role in policing licensee safety culture resurfaced. The agency incorporated qualitative insights from safety culture research into its oversight program while still acknowledging the line between regulation and management.

As the historian of the NRC, I benefitted from the advice and recollections of experts in PRA and human and

[a] A colloquialism for the useless act of teaching someone to do what they already know.

organizational factors. As is befitting my historical training, this is a work of history that applies the methods of the profession to evaluate historical sources by scholars, technical experts, and government officials to produce a reliable narrative and analysis of past events.[4–6] The NRC and its predecessor agency, the Atomic Energy Commission (AEC), have long valued and supported an agency history program that meets the standards of the historical profession.[7–13] In this paper, I have excavated publicly available NRC and industry sources, as well as contemporary news accounts and scholarly literature on human and organizational factors. What emerges is a story in which the notion and use of organizational factors and safety culture in regulation evolved in a turbulent regulatory environment of political conflict, an expanding conception of human factors, and uncertain research findings.

II. ENGINEERS AS SOCIAL SCIENTISTS: HUMAN FACTORS BEFORE TMI

Before TMI, the role of human error in plant accidents received limited attention in control room design and procedures. The AEC and NRC had to ensure nuclear power plants provided "adequate protection" to the public, as required by the Atomic Energy Act of 1954. Regulators sought to achieve adequate protection in engineering terms of compliance to rules regarding design, operating procedures, and minimum qualifications for reactor operators. Nuclear power plant licensees had to operate plants according to technical specifications that established administrative controls and safety limits on hardware and plant conditions. On paper, the roles for regulator and licensee were clear. Regulators focused on hardware safety and monitored for violations of rules and technical specifications. Licensees followed the rules and managed plant operations and personnel.

The safety importance of the "man-machine" interface—the specialty of human factors experts—was less clear and responsibility for it fell between the cracks. Neither regulators nor design firms employed human factors experts. Instead, architect-engineering firms borrowed from the functional control rooms of fossil fuel plants to create sprawling versions at nuclear plants with reliable, oversized controls and indicators spread across multiple panels and arranged for normal operations. In off-normal events, panel layout was less than optimal. Operators might dash about in haste from one panel to the next to synthesize the cascade of alarms and information into a diagnosis and select among dozens of identically arranged and shaped switches to stabilize the plant.[14,15]

By 1972, a series of mishaps made evident the risks from a poor man-machine interface. Operator errors aggravated and prolonged several routine plant transients. The AEC issued a report calling for greater attention to "human engineering" with improved control room design, operating procedures, and personnel training. Several years later, the NRC issued similar reports calling for control room design and procedures suited to accident conditions.[15,16]

The emerging field of PRA also identified the risks posed by human error. In 1975, the NRC published the Reactor Safety Study, the most ambitious PRA attempted. A major contribution was its recognition that maintenance and operator error were significant contributors to accident risk, perhaps even more than the major hardware failures postulated in the NRC's "design-basis accidents."[17]

The Reactor Safety Study observations on human error prompted the industry's Electric Power Research Institute (EPRI) to contract with Lockheed Corporation for a major study of human factors in nuclear power plant control room design. Like the previous AEC report, Lockheed found scant evidence human factors had been considered, and engineers treated human factors as a "black art." Even the most modern layouts violated basic human-factor standards. EPRI and the NRC began modest programs to study and improve human factors, but major initiatives did not begin until after TMI (Refs. 14 and 18).

Collectively, the human factors studies of the pre-TMI era revealed the limited attention paid by design engineers and regulators to the human element of nuclear plant operations. Even the scant attention paid to human factors was more than the complete ignorance within the industry of how organizational factors might contribute to an accident. Even if the industry had looked for it, there was hardly any social science research on the contributions to disaster from cultural mechanisms, ignorance, and excessive organizational confidence.[19–21]

III. TMI AND THE NRC'S FIRST HUMAN FACTORS ERA (1979–1985)

Three Mile Island validated larger budgets for research on human factors. In the first few years after the accident, the NRC's human factors research program consumed over \$20 million. The pre-TMI view of error as a product of an individual operator and his immediate environment carried over into post-TMI studies of control room design, revisions to procedures, human error studies, and accident training. There was broad agreement that the accident might have been avoided with an effective lessons-learned program, more simulator training, and intelligent control room layouts and procedures. Although organization and management issues were identified as a concern, research funding was initially limited.[12]

Calls for a more substantial study of organizational factors came from outside assessments of the accident. The presidentially appointed Kemeny Commission and an NRC-sponsored study team under lawyer Mitchell Rogovin identified management dysfunction as a contributor to the accident. Kemeny called for "higher organizational and management standards for licensees." Similarly, the Rogovin Report pressed the NRC to regulate organizational structure, human factors, and management.[22,23]

Kemeny and Rogovin prodded the NRC into forbidden territory, and agency staff tried to squirm away from direct management assessment. In late 1980, they produced broad, uncontroversial guidelines for acceptable utility structure and safety functions. The dozens of NRC licensees ranged from tiny municipal utility districts to Fortune 500 corporations. They came with idiosyncratic management structures and styles. The agency conceded evaluation would be on a largely subjective basis and promised to show great flexibility. Nevertheless, a draft and redraft of the guidelines elicited sharp criticism from utility executives that the guidelines were an "over-reaction to TMI," "unrealistic and overzealous," and "too prescriptive and unnecessarily restrictive." In search of firmer ground, the staff launched research into "safety-related management attitudes" and "organizational variables [that] can be objectively assessed" to relate "management behaviors to safety criteria through an appropriate model."[24–26]

For the first time, the NRC awarded experts in aspects of organizational management substantial funds to investigate the link between utility organizational characteristics and safety. In 1982, the Battelle Human Affairs Research Center in Seattle, Washington, contracted for a series of reports on organization and management to be developed over several years. Battelle was a think tank with deep experience in nuclear power, and it had broad multidisciplinary expertise in engineering, social sciences, and business management.

One of Battelle's first tasks was to report on how the NRC assessed management competence when staff reviewed a utility application for a new operating license. In constructing observation teams to accompany NRC staff on site visits, Battelle included human factors experts and a diversity of scholars in business management and social sciences, such as social psychology, sociology, and political science. The NRC staff review used a formal standard review plan to assess training, the structure of plant management, regulations, and staffing levels. Nevertheless, Battelle's researchers observed that staff commonly rendered subjective judgments. They lacked training in social science interview techniques or in how to perform a site assessment. A utility's reputation tended to bias the assessments, and staff strayed into unstructured, subjective questions about management culture, attitudes, and morale and drew unmeasurable conclusions, such as having "a good feeling" about plant management. Battelle argued for organization and management reviews that could withstand a legal challenge with better evaluation criteria, training, data collection, and objective performance indicators.[27,28]

The NRC also contracted with Battelle to develop a management assessment approach for plants already in operation. It analyzed two scholarly traditions of organization and management analysis. Management analysis reached back to the 1950s and studied the behavior, decisions, and processes of individual and groups of managers. Battelle favored more recent work on organizational analysis, which studied elements of an organization's environment—its size, structure, governance, reward systems, and administrative controls. By steering clear of individual management behavior and focusing on the organizational environment, Battelle expected it could develop a sophisticated "integrated sociotechnical, human machine perspective." It would avoid the subjective judgments of NRC licensing reviews and broaden the narrow perspective of engineers to include organizational factors.[29]

There was a complication in using existing scholarship for licensing oversight. Organizational research had studied business performance and managerial efficiency, not safety. Could the research measure safety performance? Battelle divided up the problem into three tasks: (1) develop objective organizational factors[b] most likely to influence safety, (2) identify a set of safety performance indicators, and (3) find correlations between the two sets. If successful, the NRC would have indicators of organization and management that predicted safety performance. If they could not, they were not useful to the NRC or licensee.[30,31]

Battelle's researchers grouped organizational factors into four categories—utility environment, historical context, organizational governance, and organization design—that were most influential of utility behavior important to safety, such as a commitment to quality, compliance, efficiency, innovation, and employee maintenance. Early analysis indicated organizational design was the most predictive of operational safety as indicated by "intermediate" outcomes that were presumed to contribute to safe operations, such as quality, efficiency, innovation, and rules compliance.[30,32]

[b] Battelle did not define "organizational factors," but current definitions capture their 1980s essence as "the organizational structures, processes, and behaviors that influence the actions of individuals at work." See S. Peters and others, "Organizational Factors in PRA: Twisting Knobs and Beyond," in the Proceedings of the 2019 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2019), April 28–May 3, 2019, Charleston, South Carolina, NRC ADAMS ML19057A474.

The first Battelle report published in 1983 offered an upbeat message that its organizational approach could solve some of the NRC's touchy oversight issues with detached assessments. Rather than the intrusive site visits the NRC used for licensing, it proposed a passive data collection model for operating plants. It would use existing, publicly available qualitative and quantitative data on utility organizational structure and plant performance from corporate reports and documents already required by the NRC. Battelle's preliminary conclusions found tantalizing indications that aspects of utility organization were linked to measured safety indicators.[33]

As Battelle expanded its research, however, the correlations were harder to discern among a fleet of nuclear power plants in which no two were alike. It was challenging enough for the researchers to determine whether an organization with many layers of management was more prone to plant mishaps than one with very few, but it was especially so as they accounted for variations in power output and reactor and steam plant designs. Nevertheless, researchers argued there was enough promise in the approach to warrant an extension of the NRC contract. The consequences of human error, it warned, were too great to ignore. "There is comparatively little opportunity for instructive learning until after dysfunctional effects have occurred." With an assessment tool that was "predictive as well as explanatory of safety," the NRC could optimize utility organization, learning, and resources; a more efficiently operated plant would be a safer plant.[34,35]

While the research was a mixture of potential and problems, Battelle's approach was politically astute in proposing a model that recognized the realities of the NRC's adversarial relationship with licensees.[36] Battelle reassured the NRC its methods would be minimally obtrusive. "Neither the NRC nor the industry wishes the NRC to become involved in the day-to-day management of the nuclear plants," Battelle observed. "This would mean active involvement in supervision and decision-making that would be unhealthy for both parties and the public safety."[37]

Battelle's careful balancing of politics and science still ran afoul of the divide between regulation and management. At a December 1982 Commission briefing on human factors programs, Chairman Nunzio Palladino expressed his discomfort with an aggressive human factors program. "I get worried when we get our tentacles out so far where we seem to be 'big brothering' every aspect of the operation . . .. I get a little uneasy when we get into peripheral aspects because . . . if we get into everything we tend to lose the initiative of the organization itself." After that, Palladino repeated the "tentacles" metaphor, and the staff promised to come back with a revised program.[38]

Issued a month later, the revised program eliminated direct research and regulatory activity on organizational factors in favor of a "more practical program capable of near-term accomplishment, as contrasted to the more academically oriented program previously described in the Plan." The Battelle studies would not be extended beyond work already in production. In 1985, the NRC went further and halted all human factors research.[39,40]

Later scholars considered Battelle's passive collection of data and focus on organizational structure shortcomings reflective of the pre-Chernobyl scholarship on organizational factors and accidents. It served as an intellectual stepping stone to research into organizational processes and culture measured through hands-on assessments with advanced psychometric surveys and interview tools.[40]

Research limitations aside, the cutbacks in human factors research reflected a changing regulatory environment during the Ronald Reagan administration of general skepticism toward regulation. There was pressure on the NRC to get back to a pre-TMI "normal." In January 1981, the NRC controller promised that by 1983 the agency budget would be "just as though there'd never been a TMI." Palladino's deference to industry initiatives also accorded with the core belief that licensees had to take ownership and personal responsibility for the safe operation of their plants. Thirty years later, former Commissioner Kenneth Rogers echoed Palladino's sentiments. Licensees, he said, must "never lose that sense of responsibility that it is their responsibility, not NRC's responsibility, to take the lead . . .. 'This is your plant, this is your facility.'"[41]

In the mid-1980s, the NRC deferred to self-regulating initiatives under the leadership of the Institute for Nuclear Power Operations (INPO). This was not the first time the NRC leaned on INPO to avoid friction with industry. The organization had taken the lead on other operational issues and training to avoid more aggressive NRC regulation. It encouraged traits of navy management "excellence." Caught between a tradition of management deference, post-TMI pressure for more active oversight, and budgetary constraints, the NRC handed the lead to INPO with a warning. "As now envisioned, NRC will not develop management and organization criteria for operating reactors unless the INPO effort proves to be unsatisfactory for our needs."[39]

IV. SAFETY CULTURE: CHERNOBYL, DAVIS BESSE, AND PEACH BOTTOM (1985–1988)

Dissatisfaction soon followed from a collection of events at home and abroad. The 1986 accident at the Soviet Union's Chernobyl nuclear power plant crystalized international

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recognition of the importance of a "safety culture" in operations, and the International Atomic Energy Agency (IAEA) became a consistent champion of developing safety culture criteria and assessment tools.[c] While supportive of safety culture discussions, the NRC also distanced its regulation and the industry from the Soviets by stressing distinctive features of the U.S. system, including safeguards against degrading operator performance and the superior safety features of light-water reactors.[42]

Events made some wonder if the NRC was drawing distinctions without a difference. Ten months before Chernobyl, a rapid series of malfunctions and operator errors at the Davis-Besse Nuclear Power Station near Toledo, Ohio, produced plant conditions uncomfortably close to TMI. The NRC concluded lax management was a significant underlying cause of the event.[43]

More disturbing were revelations at the Peach Bottom plant in Pennsylvania. In 1987, the NRC issued fines to dozens of plant operators for "inattentiveness" (sleeping) while on duty. Only a whistleblower tip alerted the NRC to the practice. Avoiding detection of plant staff, an NRC inspector turned off the lights in his plant office and hid under his desk until late into the evening. Emerging from his hiding spot, he entered the control room and caught a dozing operator. Further investigation revealed a culture that tolerated many operators dozing on shift, playing video games, reading magazines, and engaging in rubber band fights. Time magazine's headline, "Wake Me if It's a Meltdown," was humorous commentary on a serious safety culture issue. The INPO called Peach Bottom's management "an embarrassment to the industry and the nation." The NRC ordered a shutdown of units 2 and 3 that lasted over 2 years.[44–48]

Peach Bottom shocked the NRC and raised the priority of licensee oversight. Thomas Murley, who became the director of the Office of Nuclear Reactor Regulation, considered it a watershed moment that forced the agency to find a way to assess plant safety culture and rid the industry of what was called a "fossil-fuel mentality." Despite post-TMI reforms, human error and organizational factors played a role in half of all plant events. Under the leadership of nuclear navy veterans, INPO actively worked to overhaul Peach Bottom management. At the NRC, Chairman Lando Zech, a former nuclear navy admiral, announced that the NRC needed to do all it could to create a plant environment that maximized operator performance. The NRC turned to its enforcement powers to compel management improvements. In 1978, just before TMI, the NRC issued just 14 monetary penalties for regulatory violations. By 1987, it issued 114. In 1989, the Commission approved a policy statement on the conduct of plant operations that included a definition of safety culture as "the personal dedication and accountability of all individuals" to practices of plant safety and the promotion of an "environment of safety consciousness."[49–54]

V. NATIONAL ACADEMY OF SCIENCES REPORT (1988)

In the search for answers to regulatory conflict, the agency looked again to the social sciences. After a 2-year hiatus in its funding of human factors research, the NRC tried again. It commissioned the National Academy of Science's (NAS's) National Research Council to recommend a human factors program. Chaired by human factors expert Neville Moray, the NAS panel was composed of diverse membership from the nuclear industry, engineering, traditional human factors experts, business management, and the social sciences.

The panel stepped outside its mandate from the NRC and articulated a research agenda that was a significant departure for the agency and the human factors profession. The NRC's post-TMI human factors program, the panel wrote, was hindered by the pursuit of "purely technical solutions to human problems" as might be expected of the NRC's engineering culture. It observed the human factors profession suffered from a lack of imagination, too. Human factors began as a field of psychologists and engineers with the singular goal of ensuring that controls and displays appropriately matched the capabilities of humans. By the 1980s, it expanded into the optimization of personnel selection, training, and the design of habitable work environments, but the panel concluded the field needed to view nuclear power plants and other complex technologies as "sociotechnical systems" affected by organizational factors and a technology's social context. Capturing

[c] "Safety culture" was coined by the International Nuclear Safety Advisory Group of the IAEA. Initially, safety culture had a narrow definition in the research literature as one factor within a broader organizational culture. In turn, organizational culture was one of many organizational factors, such as resource allocation, training, and organizational knowledge. Unfortunately, this logical hierarchy broke down as safety culture grew into an omnibus concept that subsumed many elements once considered organizational factors. For example, the NRC's safety culture policy statement and related documents include several traits of a healthy safety culture previously seen as organizational factors. See "Identification and Assessment of Organizational Factors Related to the Safety of NPPs, State of the Art Report," NEA/CSNI/R(99)21, Vol. 1, pp. 11–21, Nuclear Energy Agency, Committee on the Safety of Nuclear Installations (1999) and S. Peters and others, "Organizational Factors in PRA: Twisting Knobs and Beyond," in Proceedings of the 2019 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2019), April 28–May 3, 2019, Charleston, South Carolina, NRC ADAMS ML19057A474.

this broader concept of human factors in research required multidisciplinary teams, including an array of social science disciplines.[55–57]

The panel called on the NRC to prioritize research into organizational and management factors. "Management can make or break a plant," Moray told the NRC's Advisory Committee for Reactor Safeguards. Even more than the man-machine interface, he said, it was essential that the NRC identify what made for a positive organizational culture of reliability and safety and develop appropriate regulatory feedback mechanisms that would reduce accident risk.[58,59]

By the time the NAS issued its report in 1988, much had changed in organizational scholarship. The NAS committee included Todd LaPorte, a political scientist at the University of California, Berkeley, who, among other researchers at Berkeley, pioneered the study of "high reliability organizations" or HROs. HRO scholarship offered a practical alternative to earlier theoretical work by sociologist Charles Perrow on "Normal Accidents." Perrow argued that technologies such a nuclear power were too complex and carried consequences too great to operate safely. Technical complexity outstripped the capacity of organizations to manage them safely. The ambition of HRO studies was to identify traits of organizations with successful records of operating in complex, high-risk environments where trial-and-error learning was not an option. LaPorte and HRO scholars typically studied organizations with military or military-like discipline, such as aircraft carrier flight operations and air traffic controllers.[60–64]

A new NRC human factors research program also stood to benefit from the maturation of social science survey tools that purported to quantify aspects of organizational culture. Through interview protocols and psychometric inventories, such as the Organizational Culture Inventory, researchers quantified an organization's cultural norms and expectations. Complementing traditional qualitative cultural assessments, the inventories quantified how an organization's members thought about attributes, such as managerial effectiveness and the quality of interpersonal relations. Extending this work to NRC licensees might allow the agency to compare licensee safety attributes through quantified indexes and to track the rise and fall of their organizational risk profile. The combination of theory, methods, and tools heralded the arrival of the social science PRA expert. Social scientists might do more than simply enlighten engineers as to the different perceptions of risk held by experts and the public; they were ready to provide direct quantitative input into calculations of accident risk. As sociologist William Freudenberg argued, if nuclear engineers wanted to improve the accuracy of their PRA calculations, they needed social scientists to help them understand and quantify human and organizational behavior.[65,66]

VI. BROOKHAVEN STUDY (1988–1995)

At the behest of Thomas Murley, the director of the office of Nuclear Reactor Regulation, the NRC tried to turn social science theory into regulatory reality. The idea was simple, if the NRC could quantify an organization's contribution to accident risk, it would have an objective basis to shut down a poorly operated plant. In 1988, the staff recommended the NAS report to the Commission anticipating that in-depth research of licensee culture could be combined with its own inspection programs to produce measures that were "predictive as well as descriptive" of degrading licensee performance. If successful, the research would become "a basis for integrating management factors into the probabilistic risk assessment PRA process, and as a basis for developing indicators of organization and management performance."[54,67]

The NRC's interest in quantifying organizational factors and safety culture set it apart from the international nuclear community's qualitative approach. The IAEA produced numerous consensus documents on a safety culture definition and qualitative assessment guidance for IAEA safety culture reviews. IAEA technical committees viewed safety culture as a search for "tangible evidence of an essentially intangible concept." It encouraged review teams to draw qualitative judgments of "attitudes, morale, motivation, and commitment to safety."[68]

In attempting to condense organizational complexities to a number in a risk calculation, the NRC program seemed like engineering naiveté, but it also reflected the regulatory and industry trend in the United States toward risk quantification. The NRC Commission and some elements of the staff placed a significant bet on PRA to reform its cumbersome and controversial regulations. In the 1980s, the agency had painstakingly assembled critical pieces of a more risk-based regulatory framework. It approved safety goals for nuclear power plants that included numerical objectives of plant risk. It completed an ambitious revision to the Reactor Safety Study, and it required plant licensees to search for plant design vulnerabilities that were typically performed with individual plant PRAs. Later in 1995, the NRC Commission added a policy statement on risk assessment more encouraging of the methodology than its cautionary statement issued in 1979 (Ref. 69).

There was still a lot of work to do to integrate PRA into regulations. The quality of utility-produced PRAs varied, and the NRC wanted high-grade products in regulatory applications. PRAs were voracious consumers of specific equipment-failure-rate data and other quantitative inputs. Yet, the data on some accident scenarios were limited and the uncertainties in risk estimates were large. Experts had to reduce these uncertainties for hard-to-quantify accident contributors, such as poor plant management.[70,71] To be useful to regulators, social scientists had to produce quantified results useful to PRA practitioners.

Across the engineering/social science divide, PRA experts were optimistic it could be done. George Apostolakis was a University of California, Los Angeles (UCLA), professor in nuclear engineering and PRA expert who went on to become an NRC commissioner. In 1989, he coauthored an editorial that captured the discipline's optimism that PRA could serve safety and resolve industry conflict. PRA had become "a kind of lingua franca of risk-related decision making . . .. We have a common language with which to discuss a particular problem area, like nuclear risk." Without it, the nuclear industry would suffer "chaos, confusion, controversy, fear, litigation, and paralysis." With "living PRAs," utilities would know accident risk at every moment of operation. Over the next few years, quantification of "morale, esprit de corps, management attitude . . . should see considerable progress." Apostolakis later recalled with a laugh, "We thought we could quantify everything."[72,73]

Brookhaven National Laboratory had a staff of psychologists, and the NRC contracted with it for a $5 million study that stretched over several years from the late 1980s to the early 1990s. Under psychologist Dr. Sonja Haber, Brookhaven worked with two other national laboratories, several institutes, and 12 universities to identify organizational factors related to the safety of nuclear power plants and to develop quantitative measures appropriate for PRA use. Apostolakis and his UCLA team were to integrate the Brookhaven results into a PRA model it designed to see if it worked.[74,75]

Brookhaven developed a structural model of a nuclear power plant's organization drawn from research by Henry Mintzberg at McGill University in Montreal, Canada. A nuclear plant organization, Brookhaven concluded, was best described as a "machine bureaucracy" with highly formalized procedures and rules, specialized groups, extensive professionalism, and a special need for safety. Investigators identified over 20 promising organizational factors under five broad categories of control systems, communications, culture, decision making, and personnel systems. Brookhaven concluded the best measurement methodologies included research surveys, behavioral checklists, structured interview protocols, and behavioral-anchored rating scales.[76]

Wary but interested, the Pacific Gas and Electric Company (PG&E) allowed a team of researchers from the University of California, Berkeley and Brookhaven to test out their Nuclear Organization and Management Analysis Concept (NOMAC) model at its fossil fuel plant at Pittsburg, California. Satisfied with their scientific rigor, PG&E permitted the team to move on to the Diablo Canyon nuclear power plant. The NRC reported hopefully that NOMAC "can be implemented in a reasonably nonintrusive manner, can be received favorably by utility personnel, and that meaningful data can be extracted for use in exploring the influences of organization and management factors on reliability and risk."[77,78]

VII. RESEARCH IN AN ADVERSARIAL ENVIRONMENT

So far, so good, but broadening the study to include the cooperation of other licensees posed a considerable challenge in the conflict-ridden regulatory environment of the 1980s and 1990s. As NRC executive director Victor Stello put it to a conference of regulators and industry, the United States had the world's most adversarial regulator-industry relationship. "We do not trust you, you do not trust us."[49,79]

Stello's was an accurate assessment. After TMI, the agency created the Systematic Assessment of Licensee Performance (SALP) to combine quantitative and qualitative assessments into a rating system of plant performance. After Davis-Besse and Peach Bottom, the agency added a capstone senior management meeting to review the performance of each plant and a "watch list" of problem plants. Plants with worrisome performance received special attention from a Diagnostic Evaluation Team (DET) that made a multiweek assessment of operations. DETs consisted of about 15 staff, including behavioral scientists, that conducted a broad assessment in areas such as organizational culture and management "beliefs, attitudes, practices . . . as well as key sociological factors." NRC staff intended to feed DET data into the Brookhaven research. Initial DET assessments, staff reported, were quite useful and utilities appreciated DET insights.[80,81]

The era of good feelings did not last. By the early 1990s, the industry had turned against DETs and the SALP. DETs were often a prelude to placing a plant on the watch list, a black eye that got upper management fired, sent utility stock prices tumbling, and required millions on maintenance and operational improvements. This oversight regime was matched with blunt enforcement tools, such as fines and plant shutdowns, that were unique among the world's regulators. Industry objected that the SALP and DETs were too subjective, a claim substantiated to a degree by the NRC's inspection guidance documents, which called for judgments on safety culture without any standards to measure it.[82–86]

The NRC leadership began to look askance at DET evaluations, too. In the late 1980s and early 1990s, navy veterans had taken over key leadership positions on the Commission and agency staff. The NRC's executive director, James Taylor, had worked under Rickover and was especially skeptical. Brian Haagensen, today an NRC inspector, worked as a contractor on DETs. He recalled that Taylor thought the DET evaluations were too aggressive, and the social scientists on the teams issued harsh grades without understanding management or nuclear technology. Taylor preferred Haagensen's firm, in part, because it was led by nuclear navy veterans, including Haagensen.[87]

The Brookhaven teams that visited nuclear plants, then worked for a regulator dubious of their capabilities and studied licensees suspicious of their motives. Rather than serve as dispassionate scientific observers, they became entangled in the research environment. In anonymous evaluations collected in 1991, they vented their frustrations. "The nature of the relationship between the NRC and the utilities permeates our role as contractors to the NRC," one researcher reported. While some utilities showed keen interest in their work, the anxiety of nuclear utilities at their presence was palpable. There was little incentive for licensees to cooperate when research findings might become burdensome regulations. "Success is failure," one observed. "The better the research on the impact of organizational factors (success), the more likely the industry will put pressure on the NRC to cut the funding for future research (failure)." The whole project, one concluded, was hindered by "the utilities' lack of trust in the NRC to use the results of our research sensibly."[88]

The scholars were even more exasperated with the NRC. Fearful of inflammatory findings, the NRC did not allow the teams to study poor performing plants or interview upper management in corporate offices. While elements of the NRC staff supported the Brookhaven project, some researchers detected from NRC management "a general distrust of the social sciences and behavioral science data." Some of the social scientists also found they could not bridge the cultural divide with engineers on their own research teams. "The gap between engineers/PRA-types and behavioral scientists does not seem to be closing very fast," one observed. Another wrote, "Social scientists in an engineering world will always have a tough time."

The research teams bridled at the NRC's restrictions. With a bit of irony, these experts in social and political sciences wanted to rid their research environment of the politics that defined it. They asked the NRC to calm utilities and remove the fetters on their access to utilities and corporate management. "The future success of this effort depends upon the cooperation of regulators, contractors, and the nuclear industry."

While the teams asked for more support, the research itself had mixed results. In a 1995 summary presentation of the project, Haber concluded the teams produced good qualitative lessons. They analyzed 20 organizational factors grouped into the four broad categories of culture, communications, human resource management, and management attention to work practices related to safety. There were connections between safety and organizational traits such as effective communication, the ability of an organization to learn, management attention to operations and safety, and the external environment of corporate and regulatory factors. They found some stable correlations between the factors, such as organizational learning and safety performance, but they could not find correlations with many others.[89]

Applying those insights to PRA did not work. George Apostolakis concluded it was almost impossible to incorporate organizational factors into PRAs. Part of the problem, as Haber recalled, was finding utilities willing to work with Brookhaven to develop more data, but survey and interview results were a difficult fit for PRA anyway. It was one thing to develop a 1 to 5 rating scale for various factors in a cultural inventory and quantify a "good" or "fair" utility organization. It was another to quantify organizational influence on equipment failure rates or human error. Haber concluded that "continued efforts to correlate organizational dimensions with performance indicators may have limited value as a nexus to safety . . .. We consider 'Culture' as a 'higher order' factor which cannot be incorporated into [PRAs]." The Brookhaven methodology was best suited for providing qualitative information for inspections and diagnostic evaluations. The NRC staff concluded Brookhaven's methodology was too resource intensive and had relatively low cost effectiveness. It recommended discontinuing research until organizational factors could be integrated into PRAs (Refs. 89 and 90).

VIII. NEAR DEATH AND THE NEW REACTOR OVERSIGHT PROCESS (1994–1999)

As the Brookhaven research progressed, industry dissatisfaction with the NRC oversight program grew. In 1994, the Nuclear Energy Institute, an industry trade organization, contracted with the consulting firm Towers Perrin to review the NRC's relationship with its licensees. It delivered its assessment just two weeks before the momentous 1994 elections where the Republican Party gained control of Congress. The report claimed the NRC was an arrogant regulator whose "current regulatory approach represents a serious threat to America's nuclear energy generating capability." Even as plant operations improved, the NRC's SALP program administered arbitrary, punitive judgments and distracted plant management with minor issues. The report provided numerous examples of trivial NRC inspection findings, such as leaving blank spaces on routine forms and poor housekeeping that missed dust bunnies behind a plant telephone. Special inspections such as the DETs were "inflammatory, inflated, and not constrained to fact."[91]

As the industry expressed its dissatisfaction with the SALP, poor performing plants made headlines. A whistleblower at the Millstone nuclear power station made the cover of *Time* magazine. The NRC ordered the shutdown of all three Millstone reactors. Millstone unit 1 never produced electricity again, and the utility spent over $500 million on upgrades and reforms to get unit 3 back on line 2 years later. In 1 year, the number of plants on the watch list jumped from 6 to 14 (Ref. 92).

A turning point came in 1998. With the support of his subcommittee, Republican Senator Pete Domenici, a champion of nuclear power, forced the NRC to abandon its SALP process by threatening cuts to 700 staff. The NRC's "near death" experience led to the creation of a new Reactor Oversight Process (ROP) that spelled out "cornerstones of safety" keyed to more quantitative indicators of safety performance. NRC resident inspectors remained a bedrock presence in the ROP, as they were in the SALP, but their findings and evaluations of plant events were, as much as practicable, quantified and categorized by their safety significance. Plant operations were evaluated by comparing performance indicators against prescribed risk-informed thresholds. By accounts from industry, NRC veterans, and even nuclear power critics, the ROP was more objective than the SALP, less adversarial, and still resulted in significant improvement in the safety performance of the U.S. nuclear fleet. The ROP was part of a broader effort to "risk-inform" regulations by supplementing traditional qualitative indicators of safety with more quantitative measures. As the quantification of performance indicators grew in importance, however, some qualitative assessments were left behind. "That was the end of the DETs," recalled Brian Haagensen.[87,93–95]

The NRC's inability to translate social science research into a practical tool aligned with similar frustrations among academics who studied safety culture. In 1998, Nick Pidgeon, a psychologist and safety culture scholar at the University of Wales, assessed the fracturing of safety culture research along disciplinary, theoretical, and practical lines. "Some 10 years on from Chernobyl, the existing empirical attempts to study safety culture and its relationship to organizational outcomes have remained unsystematic, fragmented, and in particular underspecified in theoretical terms." Engineers wanted a "best" solution, but social scientists had only managed to raise "the thorny issue of whether culture can be 'measured' at all using quantitative psychometric methodologies such as questionnaires or surveys . . .. If the theoretical fragmentation of the field is not overcome, commentators will conclude that the work failed to realize its considerable promise." The term "safety culture," he lamented, might turn into "hollow rhetoric that pays lip service to safety."[96]

As it entered the twenty-first century, the NRC did not explicitly regulate safety culture in the ROP. Unable to quantify organizational factors, the ROP inferred them indirectly from other performance indicators, such as the number of unplanned plant shutdowns. The INPO took the lead on inculcating safety culture among licensees. In 2004, George Apostolakis presented a gloomier assessment of safety culture quantification than he had in 1989: "Defining indicators of a good or bad safety culture in a predictive way remains elusive. [PRAs] certainly do not include the influence of culture on crew behavior and one can make a good argument that they will not do so for a very long time, if ever."[97–100]

The Brookhaven methodology went into exile. The Atomic Energy Control Board of Canada (AECB) was interested in the NRC-sponsored research. Haber left Brookhaven and with Dr. Michael Barriere adapted the NOMAC model to reflect advances in methodology and research. Interested in the methodology's qualitative insights, the AECB simply required it be practical, generate reliable results, and develop an accurate picture of nuclear plant operations. While the Canadians applied the model to numerous facilities, they found it was, as the NRC had previously, a resource-intensive tool. Spain investigated a similar model.[101–103]

A few countries, such as Switzerland, Finland, Germany, Canada, and Spain formally established safety culture regulations or required operators to perform safety culture self-assessments. Most other nations adopted policy statements where safety culture appeared as a major theme or stated key traits that constituted a good safety culture.[102,104]

IX. DAVIS-BESSE AND A NEW APPROACH TO SAFETY CULTURE (2002–PRESENT)

As safety culture gained some currency abroad, the Davis-Besse nuclear power plant suffered an event in 2002 that forced the NRC to revisit its deference to the nuclear industry on the issue. During plant maintenance, workers discovered substantial erosion in the 6.5-in.-thick reactor vessel head. Cracking in reactor control rod components led to the escape of corrosive borated water and steam, which scoured a hole in the vessel the size of a pineapple. Only a thin stainless steel liner on the inside of the vessel head prevented a loss-of-coolant accident.[105]

It was the most significant safety event in the United States since the TMI accident. First Energy Nuclear Operating Company (FENOC) had taken over operations from Toledo Edison Company and enjoyed a reputation as a top performer. Its fall from grace was dramatic. It lost hundreds of millions in revenue, including $33.5 million in criminal and civil penalties. Some plant staff were convicted in federal court of concealing information from the NRC about degrading plant conditions. Davis-Besse indicated that a plant could meet the good "green" column rating of the ROP performance indicators while not revealing a plant culture that prioritized efficiency over safety. The public and Congress asked tough questions: Why had the licensee's safety culture degraded? Where was plant management? Where was the INPO? Where were NRC inspectors? Sixteen years after Chernobyl, why didn't the NRC have a safety culture regulation?

As a condition of restarting the plant, the NRC required the licensee perform its own assessment of plant safety culture and contract for an independent safety culture assessment. Sonja Haber led a team of consultants that included Valerie Barnes and veterans of the nuclear navy. Using an updated version of the methodology and survey tools of the Brookhaven study, the team assessed FENOC by widely agreed upon IAEA safety culture characteristics: (1) recognition of the value of safety, (2) integration of safety into all plant activities, (3) accountable for safety, (4) learning-driven safety, and (5) clear leadership for safety. Despite improvements, the team concluded, FENOC had made only partial progress toward those characteristics. FENOC spent several years conducting additional safety culture assessments.[106]

The episode opened the NRC to attacks that it was a reluctant convert on safety culture. David Lochbaum of the Union of Concerned Scientists and Paul Gunter of the Nuclear Information and Resource Service penned an analysis entitled "NRC has a brain, but no spine." They claimed the NRC worried more about the financial health of FENOC than serving as an independent regulator. The NRC did not fare much better on Capitol Hill. Ohio Senator George Voinovich pressed NRC Chairman Nils Diaz: "Why do you disagree with everyone that you should put in place a regulation to monitor safety culture? Why do the Europeans do it? You are going to be [doing safety culture assessments at] Davis-Besse for the next 5 years . . .. Why [don't we] make that applicable to all the facilities?" Echoing Nunzio Palladino's reservations 20 years earlier, Diaz's replied, "Because it will get into an area that the Commission believes that we should not be, which is managing the facility."[107,108]

The sum of operational events since TMI broadened the NRC's thinking on safety. Its fundamental safety concept, defense in depth, evolved from an almost exclusive focus on design safety to a multilayered system of plant defenses including design, organizational, and human elements. And, while the NRC did not develop a safety culture regulation, it inserted a little qualitative judgment on safety culture into its ROP. In 2006, NRC psychologists, such as Julius Persensky, collaborated with other technical staff to create opportunities for inspectors to diagnose and act on safety culture weaknesses, a process to determine the need for an evaluation of a licensee's safety culture, and guidance on evaluating and conducting an independent assessment. To Valerie Barnes, a recent addition to the NRC staff, integrating safety culture into the ROP seemed misguided because NRC inspectors—engineers—would judge safety culture a job for social science experts. Nevertheless, she and other human factors staff helped establish appropriate protocols in the ROP and the language of the NRC's safety culture policy statement, which was approved by the Commission in March 2011 just days before the accident at the Fukushima Daichi nuclear power plant. The final product, she thought, captured the important elements of safety culture.[109–111]

X. CONCLUSION

The NRC's research and regulation of organizational factors and safety culture has been shaped by the intensely adversarial relationship that developed between the NRC and its licensees in the post-TMI era. Conflict gave social scientists a unique opportunity to influence regulation, but it also erected substantial roadblocks. Mishaps in the nuclear fleet and cases of unprofessional behavior forced the NRC outside of its carefully defined oversight boundaries into the unfamiliar territory of assessing licensee management competence. Armed with new theories on organizational behavior, social scientists seemed poised to demonstrate their practical relevance to the engineers who dominated safety regulation. An adversarial relationship, however, demanded assessment by unambiguous, objective data and methods, a task that did not play to the qualitative strengths of social scientists. Applying their insights has required a delicate balancing of quantitative and qualitative factors, even in the current era of limited regulatory conflict.

The NRC's ambition to quantify organizational factors remains one of PRA's "grand challenges." PRAs still do not explicitly model their contributions. Disagreement exists in how organizational factors are measured and translated into PRAs. There are not yet data demonstrating a causal link between organizational factors and human error or equipment failure rates. If PRAs are to provide the predictive capability the NRC seeks, these challenges will need to be overcome.[112,113]

The inclusion of safety culture in the NRC's ROP has also produced mixed results. It is clear organizational factors have had important influence for pro-active design and operational improvements that optimize plant response to incidents, and case studies show they play a role in plant events. Demonstrating their contribution to regulatory oversight has been more difficult. In 2014, NRC staff found the inclusion of safety culture in the ROP added little safety value and was resource intensive. Another study conducted by NRC and INPO human factors experts, however, found an empirical link between safety culture and safety performance. The authors recommended further research to confirm that the relationships they found remain consistent over time.[114,115]

Almost 40 years after human factors experts joined the NRC, the goal of quantifying organizational factors predictive of safety remains a long-term ambition. How have social scientists contributed to the NRC's understanding and regulation of safety culture? As was evident in this story and has been noted elsewhere, the social sciences brought to the search for safety an unprecedented level of interdisciplinary research and have promoted key safety culture traits discovered in their research, such as an organizational learning culture, and have established safety culture as a set of personal and organizational traits with a logical structure. Human factors specialists have worked with engineers and the industry to articulate a common language for use in safety culture assessments. There is a similar effort to harmonize safety culture language across multiple international organizations and foreign languages.

That common understanding of safety culture may be their most important contribution. The NRC's engineers set out to turn the cultural concept, safety culture, into the quantitative language that PRA specialists understood. Instead, human factors specialists taught the nuclear industry to think and speak of safety culture in the qualitative language that can be understood by social scientists and the public.[116–122]

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