SAFE SCIENCE:

MATERIAL AND SOCIAL ORDER IN LABORATORY WORK

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Published in *Social Studies of Science*, Vol. 35, No. 3 (June 2005): 333-366

Abstract

Scientific laboratories can sometimes be dangerous places to work, and safety concerns can have a significant impact on the scientific research. Because safety practices specify both behavioral norms and technical standards, they provide an opportunity to better understand the relationships between the organizational and epistemic aspects of scientific culture. This paper presents a case study of a ‘pulsed power’ facility at the U.S. Los Alamos National Laboratory where electrical hazards are a major concern. Drawing on work by Mary Douglas and others, I show how safety in the pulsed power laboratory can be understood in terms of concepts of order and pollution. In particular, I argue that the laboratory is a cultural setting that generates both material and social order in science. The concept of ‘traceability’ – the ideal of being able to trace visual and logical connections between system components – is the central metaphor for material order in this setting. This metaphor is enacted in the design of pulsed power systems and through various safety procedures that function as rituals. These rituals, and the concept of traceability itself, also contribute to social order by helping to shape norms of conduct in the laboratory, which in turn structure relationships between the laboratory work group and the larger institution.

Key words: laboratory, safety, risk, norms, ritual

There is surely no more useful skill in the practice of scientific research than the knack for not accidentally killing oneself with the laboratory equipment. One of the accomplishments of science studies, and particularly studies of scientific laboratories, has been to advance the notion that the mundane activities and skills of laboratory work can be epistemologically relevant.[1] With this in mind, laboratory studies have made a serious effort to understand various mundane activities and their role in the creation of scientific knowledge. Yet the risks of laboratory work, and the safety efforts and skills necessary to overcome them, have rarely been a focus of attention in laboratory studies. Perhaps we tend to think of safety as a bureaucratic function, rather than as a body of practice immediately relevant to the production of knowledge. It is true that safety can be a heavily bureaucratized and organizationally complex issue. But issues of risk and safety can also be an integral part of the practice of science, and can pose significant epistemological problems. It is partly because of this dual nature – organizational and epistemological – that laboratory safety is an important topic for science studies. It brings up neglected connections between scientific knowledge and the cultural norms of science, as both are produced and reproduced at the level of scientific practice. This paper shows how, in one laboratory, safety appears as an object of epistemological concern, as a central organizing principle of group culture, and as a resource for defining the relationship between the research group and the larger institution in which it is situated.

Safety can pose epistemological problems in a laboratory setting in part because safety efforts are not easily abstracted from the processes that produce scientific knowledge itself. Safety can be understood as an effort to order the environment in such a way that danger is eliminated or contained. In the course of research, scientists are already engaged in a struggle to create order – to understand, predict, and modify the behavior of objects of study as well as the machines and instruments used to study them. Likewise, safety depends on understanding, predicting, and modifying the behavior of potentially dangerous research apparatus and objects of study. As a result, work safety in a particular research field is, in part, dependent on the evolving body of knowledge generated by research in that field.[2] More generally, the set of technical skills and knowledge necessary to make equipment function safely is largely the same as that required to make it produce reliable scientific results. In safety-critical scientific environments, safety efforts and research work are interdependent processes that can demand congruent or conflicting forms of order. Safety concerns can significantly limit or alter research programs, and new research directions can generate major changes in the way safety is defined and maintained. Safety is an epistemic problem and it can have epistemic consequences.

Safety makes connections between scientific knowledge and the larger cultural and organizational context of science. One reason for this is that safety efforts characteristically blur the line between technical practice and moral prescription. Safety rules set technical standards as well as behavioral norms. While other forms of risk discourse may tacitly encode normative judgments, safety discourse is explicit in its specification of the ways people and machines should behave in response to possible danger. It freely mixes normative and technical language to an extent that is unusual in other forms of technical discourse. Safety discussions can revolve around everything from physics and engineering calculations to organizational structures to considerations of the values and moral character of individuals.

Another key feature of safety is that it typically grounds this diverse set of considerations in a very concrete institutional context. There are many informal forms of workplace discourse that mix technical and normative language, revolving around notions like status, skill or experience, for example. These issues bring out connections between scientific work and moral order, but if they are not examined in relation to organizational structures, they don’t tell us much about the institutional context of science. Because safety is typically an organizational function, it provides opportunities to consider how scientists situate research, as a moral and technical enterprise, in relation to the very different normative context of bureaucracy. This brings issues of scientific identity and cultural boundaries into sharper focus.

Safety is an important topic not only because of it touches on key issues in science studies, but also because it is an increasingly salient issue in many scientific research settings. Since at least the middle of the twentieth century, scientific work has come to involve increasingly exotic chemicals, biological organisms, and forms of radiation, and has generally become more industrial in character. Social changes have also forced scientists to pay more attention to safety in the workplace. Governments of the United

States and other industrialized countries became much less tolerant of workplace and environmental hazards through the twentieth century, a transformation that has been reflected in an enormous expansion of government regulation of workplace safety, occasional efforts at regulatory roll-back notwithstanding.[3] In industry, there is a recent trend toward extending workplace safety efforts to new kinds of work, including administrative and professional tasks. This trend is now beginning to affect universities and government research laboratories as well. As a result, scientists find that they are increasingly being held formally responsible for the safety of research facilities.[4]

One interesting recent development in the field of occupational safety has been the increasing popularity of a vaguely cultural view of safety – in particular, the concept of a ‘safety culture’.[5] This paper, too, takes a cultural perspective on safety, but it is conceived more in reaction to this trend than as an extension of it. The concept of ‘safety culture’ as used in the safety literature is problematic for two reasons. First, it appears to have been developed in almost complete isolation from social scientific ideas of culture, and therefore fails to recognize many of the complexities that have emerged in anthropological and sociological studies of culture and cultural change. Second, it is an explicitly normative concept: a ‘safety culture’ is one that possesses certain cultural characteristics deemed necessary for workplace safety. However, there appears to be little empirical work to back up the effect of these cultural characteristics on safety. When I use the term ‘safety culture’, I use it primarily in a descriptive sense: a group’s safety culture simply describes those aspects of its culture that relate to safety. In taking this perspective, I subscribe to and expand on a social scientific idea of culture that takes into account the full complexity of the relationships between the conceptual, normative, and material aspects of culture and the symbolic load they carry.[6]

Safety and Order

Danger is one of several concepts that can be grouped in the cross-cultural category of pollution beliefs, which also includes ideas about dirt and defilement. The work of anthropologist Mary Douglas provides a key set of analytical tools for understanding pollution beliefs and their relationship to knowledge and social structure. Douglas argues that pollution beliefs, in all their forms, emerge out of a culture's ideas about order and disorder. Safety, cleaning, purification, and related practices keep disorder and pollution at bay and simultaneously impose a positive, normative order on the environment (Douglas, 1966: 2). Two key aspects of Douglas's arguments about the connection between pollution and order are particularly relevant here. First, pollution beliefs are connected to ideas about the proper order of the material world. Second, pollution beliefs are used to sanction certain forms of social order. The laboratory study presented here discusses safety in terms of these two issues.

Material Order

Douglas discusses the relationship between pollution beliefs and material order primarily in terms of the concept of dirt. She uses contemporary Western beliefs about household cleanliness as her central example. In Douglas's view, our ideas about home entail certain beliefs about what activities should occur where, and what kind of material things are appropriate to certain areas of the house. Dirt, or messiness, occurs when certain objects or materials cross these boundaries and end up in the wrong area:

> Shoes are not dirty in themselves, but it is dirty to place them on the dining-table; food is not dirty in itself, but it is dirty to leave cooking utensils in the bedroom, or food bespattered on clothing; similarly, bathroom equipment in the drawing room; clothing lying on chairs; out-door things in-doors; upstairs things downstairs; under-clothing appearing where over-clothing should be, and so on. (Douglas, 1966: 35-36)

More generally, Douglas argues that ‘dirt is the by-product of a systematic ordering and classification of matter, in so far as ordering involves rejecting inappropriate elements’ (Douglas, 1966: 36). Our ideas about workplace danger tend to be similarly organized: danger is frequently associated with failure to respect appropriate spatial boundaries, and on the safety side, much effort is put into the installation of barriers, interlocks, and procedures designed to keep the human body from coming together with other material things in dangerous ways.

The possibility of pollution not only arises when clear boundaries are crossed, however. Another potential source of danger is ambiguity or anomaly. Things that don’t fit existing categories – what anthropologist Victor Turner (1969: 94-130) calls ‘liminal entities’ – may be labeled dangerous. Situations in which categories are uncertain may also be seen as dangerous. For example, cleaning and maintenance of industrial equipment can be a particularly dangerous activity because the usual physical barriers and rules that separate people from dangerous parts are often bypassed. In such situations, various rituals or procedures may be employed to re-establish the relevant boundaries or remove anomalies or ambiguities from the system (Douglas, 1966: 36-40; 94-95).[7]

Social Order

Douglas describes the interaction between pollution and social order as occurring at two levels. At the more concrete level, pollution ideas can be used to police social boundaries:

> The ideal order of society is guarded by dangers which threaten transgressors. These danger-beliefs are as much threats which one man uses to coerce another as dangers which he himself fears to incur by his own lapses from righteousness. They are a strong language of mutual exhortation. (Douglas, 1966: 3)

Beliefs about danger are particularly powerful because they don't usually take the form of explicit moral prescriptions. Rather, some dangers are seen as the inevitable result of certain behaviors, objectively demonstrating the incorrectness of those behaviors. Contemporary ideas about workplace safety are based on this assumption: workers are exhorted to follow safety rules not just because violations may be punished administratively, but because they may be physically harmed by impersonal forces if they do not follow the rules. At a more conceptual level, Douglas (1966: 3) notes that pollution beliefs can serve as 'analogies for expressing a general view of the social order'. At this level, safety practices can be seen as expressing general beliefs about the proper relationship between worker and employer, or about norms of interaction between co-workers.

Order in the Laboratory

Studies of scientific work have shown that scientists employ various practices to structure a chaotic natural world in a way that permits orderly scientific investigation. Systems are rigorously separated to prevent cross-contamination; materials are separated, measured, and sorted into categories; beams are carefully focused and calibrated. Laboratories, in particular, are key locations where scientific forms of order are generated and exploited by researchers. Scientific ideas about order structure the laboratory environment and workplace in fundamental ways. Safety practices also express a particular vision of order, which itself is often expressed in scientific or engineering terms. Because of this, safety practices can intersect with, or collide with, scientific work practices and affect the production of scientific knowledge in interesting ways. Scientific work practices also imply a certain view of the social order of research work. This scientific vision of social order is sometimes not made explicit in laboratory studies, but it is arguably a key element of the normative structure of science. Because safety discourse makes many of its normative assumptions explicit, interactions between science and safety also help expose the normative structure of scientific work.

Others have touched on the relevance of Mary Douglas's work to the issue of laboratory safety. Work by Peter Galison on the impact of safety issues on the history of high-energy physics, and by Cyrus Mody on concepts of order and contamination in a materials science laboratory, is particularly relevant.[8] However, these authors each touch on safety incidentally, as part of larger descriptions of laboratory work. They also focus on safety primarily as an imposition of a certain kind of bureaucratic vision on science. Working scientists are depicted primarily as resisting this bureaucratic effort. There is clearly a great deal of truth in this portrayal: the scientists and technicians I talk about in this paper were extremely skeptical of institutional efforts to impose safety rules on the laboratory workplace, particularly where they regarded those rules as disconnected from the realities of scientific work. But they also pushed me to look at laboratory safety in a different way. Regardless of their views on safety as an institutional matter, safety was something they placed great value on and devoted much effort to in their work. Because they worked in an environment they recognized to be highly dangerous, safety became a matter of direct personal concern – literally, a matter of life and death. For them, safety was no mere bureaucratic imposition, but rather a central animating principle of laboratory culture. In particular, they viewed safety as an integral part of the technical work of research. Here, I take this view of safety as my starting point. By examining the continuities between safety and the broader realm of scientific practice, I hope to provide a better understanding of the true epistemological and cultural significance of laboratory safety.[9]

Los Alamos and Pulsed Power Culture

Los Alamos is widely known as the place where the first nuclear weapons were developed. The current Los Alamos National Laboratory (hereafter LANL or the Laboratory) is a U.S. government research facility operated under the authority of the Department of Energy, and still exists primarily as a nuclear weapons research center.[10] However, the Laboratory is managed by the University of California and supports a great deal of basic research. Some of this research, such as in the biosciences, is not related to nuclear weapons at all, though it typically has some relevance to national security. Other research, in areas like plasma physics, has grown directly out of the Laboratory's weapons mission, but is oriented toward the development and communication of scientific knowledge to a broader research community. Though there are many of them at the Laboratory, such basic researchers have a somewhat ambiguous place in the status hierarchy: they feel they do not get quite the institutional respect accorded to researchers in the core 'weapons program', yet the open nature of their work gives them more access to professional rewards outside the Laboratory in their respective scientific fields. Focusing on these researchers gives a different perspective on the scope of scientific activities at U.S. weapons laboratories, while providing a basis for findings that may be relevant to a wider scientific community.

This paper's argument is grounded in nearly two years of research on safety practices at basic research facilities at LANL, with the aim of understanding how scientists and technicians integrate safety into their work practices. This research included intensive ethnographic study of two different research areas: bioscience and plasma physics. The bioscience study involved observation and interviews with several research teams engaged in relatively routine, low-hazard work. For the plasma physics study, I conducted interviews and engaged in participant observation as a laboratory worker in a plasma physics research facility in which the potential hazards – and corresponding safety efforts – were much more significant. The latter facility is the focus of this paper because, as a relatively high-risk environment, it provides many clear examples of the interactions between safety and the scientific research process. To preserve anonymity, I refer to it here simply as the Plasma Lab.

The members of the Plasma Lab work together in ways that are typical of many scientific laboratories. Work at the laboratory is directed by two senior researchers, who have extensive experience in plasma physics, both inside and outside academia. These scientists are principal investigators for the research projects that fund the facility. Most of the daily work of getting equipment ready and carrying out experiments and tests is supervised by a core group of postdoctoral and junior researchers. These researchers perform some of the work that would likely be performed by graduate students in a university setting. However, there are usually several high school or college students working in the laboratory. Some come in through various cooperative study or vocational programs, and many are children of LANL employees who come to work during a summer or semester off. In part because of the lack of a large student workforce, technicians play a large role in experimental work at Los Alamos. The Plasma Lab employs several technicians. Some are experts in the design and fabrication of laboratory equipment, while others are skilled in more purely hands-on work.[11]

The Plasma Lab is located in a rather nondescript building that looks like it might be a small warehouse. Inside the building, the lab occupies an open area of roughly 700 square meters with 10-meter ceilings. Walls divide the floor space into offices and other rooms, but the rooms are open to the high ceiling above. The entire space is lit by bright lights mounted on the ceiling, and noise echoes throughout, lending the building an industrial feel.

Most of the research activity at the Plasma Lab takes place in the central area of the facility, a large experimental space that is bounded by taller, reinforced walls, though it is still open to the rest of the lab from above. This space is filled with a complex, interconnected collection of scientific equipment that is difficult to make sense of at first. There are several seven-foot-high metal racks, each holding six to eight shiny metal boxes. In the center of the room sits an experimental apparatus: a compact set of squared-off metal coils surrounding a glass cylinder about three feet long, which is attended to by a variety of cables, tubes, pumps, and measurement instruments. The coils are attached to a pair of large, horizontal metal plates about 4 meters across. The plate is connected to the racks and other equipment by inch-thick cables that run through overhead channels. Within this complexity one also begins to notice a number of artifacts that look like they've been appropriated from a B-movie mad scientist's laboratory: large glass tubes mated to burnished copper elements; pairs of curved metal electrodes encased in Lucite boxes; plastic tubs of water connected to electrical cables. In a surreal touch, parts of some of the larger pieces of equipment are wrapped or loosely draped with layers of translucent plastic sheeting.

This specialized configuration of equipment is characteristic of 'pulsed power' technology. The racks full of metal boxes are capacitor banks.[12] The various strange-looking high-voltage switches are used to discharge the capacitors simultaneously and very suddenly. This generates a huge pulse of electrical current which travels through the thick cables, into the metal plates, and around the coils, creating a very large magnetic field in the process. To give an idea of the amount of current that can be involved, I was told that one pulsed power system at LANL is capable of generating a very, very brief pulse of 33 megaamps, which, for that instant, is supposed to be roughly equivalent to the entire current output of every electricity generator on the planet. The Plasma Lab apparatus is significantly smaller: it can generate maximum currents on the order of 100 kiloamps at 50 kilovolts, and its capacitors can store roughly 200 kilojoules of electrical energy when fully charged.[13]

The character of this technology, as much as the scientific subject matter, seems to structure work, and danger, in the Plasma Lab. The lab is part of a larger pulsed power technical community that cuts across various specific research fields within the larger discipline of physics. The intense electrical and magnetic fields a pulsed power system generates can be used to energize and confine plasmas for fusion studies and to implode metal shells in weapons research; the technology can also be used to power lasers and particle accelerators. Pulsed power technology has flourished primarily at government laboratories and private R&D firms, but is currently developed in university settings as well.[14]

The scientists and technicians I studied emphasized the unique technical challenges involved in operating a pulsed power system. Because of the currents involved and the need to discharge the pulse almost instantaneously, these systems use a unique array of switching devices, many of which are based on vacuum tubes or involve the deliberate production of electrical arcs. The systems must be designed to stand up to large currents and the mechanical stresses caused by strong electromagnetic fields. Components have to be arranged to prevent arcing through the air or along surfaces between them, even though these discharges can be difficult to predict.[15] It is a further challenge to design instruments and data acquisition systems so they are adequately shielded from the electromagnetic fields generated by the pulsed power circuitry. All of these factors make designing and running pulsed power systems very specialized technical work. I was told that becoming skilled in this area requires experience not easily acquired elsewhere, even in other types of electrical work.

Because of the high voltages, large currents, and the sheer amount of stored electrical energy involved, everyone agrees that pulsed power work has the potential to be very dangerous. Coming into contact with the electrical equipment when it is charged could, of course, lead to a shock or electrocution; but I was warned that a fully-charged capacitor bank can shock a person who comes *near* it by sending an arc through the air. When a pulsed power system is in use, an electrical fault can lead to catastrophic failures of components: capacitors can explode, cables and connectors can be blown across the room at high velocity; air arcs between components can happen with explosive intensity. If the automatic grounding system is damaged, capacitor banks can end up electrically isolated at high voltage. In such cases, a manual ‘shorting stick’ must be used to ground them; if done incorrectly, this can cause a sudden, explosive discharge. Even in normal operation, the high magnetic fields generated can propel loose metal objects across the lab. On top of all this, the experimental apparatus that all the electrical energy is pumped into may be designed to implode or reach very high temperatures, and laser- and x-ray-based measuring instruments can pose hazards in their own right.[16]

A distinctive work culture has evolved around pulsed power technology at Los Alamos. This culture appears to be built around the sense of working with something powerful and dangerous, and emphasizes the peculiar and demanding nature of pulsed power work. I found safety to be a central concept in this culture. Workers, both scientists and technicians, discuss safety frequently while building and operating pulsed power systems, and emphasize their dependence on one another in safety matters. They talk about the need for ‘ultimate respect for pulsed power’ because it ‘absolutely for a fact can kill you’.[17] They observe that ‘you don’t, you know, get the opportunity to make a second mistake’.[18] Experienced scientists and technicians press this message on newcomers with stories about pulsed power accidents that emphasize the unpredictability, power, and lethality of the technology. There is not much joking about safety issues, unless it is to make fun of someone’s incompetence or lack of commitment to safety. Those who seem willing to compromise real safety (as opposed to certain institutional safety rules) for the sake of scientific productivity are generally seen as deviant, not heroic. When conflicts arise between colleagues, they are often over differing opinions on safety issues. Whether colleagues are trustworthy and competent is something people actively worry about. Not surprisingly, there is some distrust of outsiders or new people in the workplace. In safety matters especially, pulsed power workers can be dismissive of colleagues, managers, or safety personnel who have demonstrated incompetence or lack of insider knowledge of pulsed power work.[19] However, prospective members of the community do not seem to be put in dangerous situations to test their abilities. The price of admission to this community, as I discovered, is to exhibit risk-aversion and deference to more experienced colleagues.[20] Unlike the scientific communities studied by Mody and Galison, this community does not appear to view safety primarily as an imposed regime of surveillance and control. Members of the community do talk about safety rules this way when they are imposed from the outside, but they also treat safety as a positive organizing principle that enables them to exercise control over their work environment.

Some of what I have described may strike some readers as surprising in light of historical accounts of the 'cowboy' mentality about risk in Manhattan-project era Los Alamos.[21] There do seem to be some continuities between early Los Alamos culture and the present culture of pulsed power work at LANL, but the attitude toward safety has changed substantially, in part because the Laboratory is increasingly subject to regulatory scrutiny. In the early 1990s, the Department of Energy dispatched so-called 'Tiger Teams' to all the National Laboratories to carry out a massive safety audit that identified thousands of cases in which LANL was not in compliance with Department safety rules. Though this audit was seen as bureaucratic overkill by many, it did elevate safety to a much more prominent role in laboratory life. Ironically, the complexity and difficulty of this audit process spurred both the Energy Department and the National Laboratories to seek new approaches to regulating safety that emphasized extensive local documentation of safety rules with a great deal of bottom-up technical input from scientists and other workers. These procedures are now codified under the rubric of 'Integrated Safety Management' or ISM. Under ISM, research facilities have to develop their own ‘Hazard Control Plans’ in which they list potential risks and safety procedures to mitigate those risks. Many scientists and technicians see this as unproductive bureaucratic intrusion into the workplace, but it has made safety a much more salient issue for research workers across the Laboratory. The safety culture of the Plasma Lab, and of pulsed power research in general, seems to have been well in place before these institutional changes took place. In fact, this kind of safety culture is just what ISM is supposed to foster. Interestingly, this fact seems to have made pulsed power workers more, rather than less, skeptical of ISM and institutional safety personnel, at least in the short term.

Traceability: A Metaphor for Material Order

In the Plasma Lab, safety practice is integrated into the broader arena of scientific practice through a distinctive way of attending to laboratory space that I call *traceability*.[22] This concept specifies an ideal standard for how material components of laboratory systems ought to relate to each other so that researchers can work effectively and safely in the laboratory environment. The need for traceability stems from the desire of laboratory personnel to have access to a complete picture of the state of the pulsed power system at a given time. This includes knowing about the state of system components and the integrity of the connections between them. Traceability is the set of system characteristics that makes this knowledge easy to obtain. In particular, it breaks down the ideal of material order into a set of conventions that generate *visual* and *logical* order in a system.

Pulsed power culture in general emphasizes acute visual awareness of one's surroundings as an important aspect of both technical competence and safety. The gist of this concern is expressed metaphorically in a story one of the scientists told me about researchers at a pulsed-power laboratory in California. They were doing diagnostic work near some fully-charged capacitor banks (clearly operating under looser safety guidelines) when an earthquake hit, shutting off all power and lighting in their windowless facility – but leaving the capacitor banks charged. The scientist telling the story laughed as he described the scientists sitting in the dark, trying desperately to orient themselves and figure out which way they could safely move. The fact that the scientists couldn't see, rather than the physical damage from the earthquake, was the focus of tension (and humor) in this story.[23] More concretely, one technician reflected that:

> To me the good experimental operators were the ones that could see the whole aspect of the experiment from air pressures, to water temperatures, to the conditions of the banks, to whether the tools were put up or not, to whether somebody had left a door open, or forgot to hook a cable … I mean they just developed this knack for seeing problems.[24]

This remark describes this kind of total visual awareness of the laboratory environment as a skill that is learned through experience. However, researchers also put a great deal of effort into ordering the laboratory environment itself to make this kind of awareness possible. As I will describe in more detail below, they employ a variety of visual devices to mark system components or render them open to inspection. These are meant to make it possible to more readily make visual sense of the laboratory from a safety and general operational standpoint.[25]

When I started asking people about safety in the Plasma Lab, initial discussions often revolved around the issue of messiness or clutter.[26] As in the household context discussed by Douglas, close examination of these concepts provides some insight into underlying concepts of order – in this case, traceability. At one level, people had quite different perspectives on whether or not the laboratory was basically orderly. Some felt that it was unacceptably cluttered:

> You have, basically, three or four little experiments all shoved into the same room, which it wasn't designed for. So you've got a lot more stuff in a smaller area, so it's going to be more hazardous.[27]

Others found it to be quite tolerable in this regard:

> This room out here is very clean and ... compared to a lot of the experiments I've been involved with, this is a very good work space ... you know, it's clean, it's well lighted, it's not really cluttered, people take good care of their tools.[28]

Regardless of their view of the facility, however, people seemed generally to agree that clutter is a safety problem – in part just for the obvious reason that it makes it more difficult to maneuver around the equipment, and increases opportunities for tripping or running into things. But on further discussion, it became clear that the people I talked to viewed clutter as something more than just having too many things in too little space. Instead, they thought that clutter was something that had to be defined relative to the nature of the experiment:

> The more complicated it gets ... things just have a tendency to get more and more ... maybe clutter isn't the right word, because a lot of stuff happens around the [experimental apparatus] coil ... diagnostic[s] are there, a lot of cables leading out from that ... even if people are as careful as they can be, there's gonna be a place where there's lots of stuff ... that doesn't mean people don't care or they're not trying real hard, that's just the way the experiment has to [be].[29]

Here, a distinction is made between clutter and something else that could perhaps be called complexity. The point seems to be that experiments are inherently complex, yet this doesn't necessarily make them cluttered or unsafe. Other interview subjects expanded on this further, arguing that the real issue was whether the complexity was organized in a way that made sense from a scientific or safety standpoint. One scientist made the distinction that 'an experiment can be crowded, but it can be logically well organized too', offering 'evidence that somebody knew what they were doing when they put it together'.[30]

The metaphor of traceability places these concerns about clutter and logical order in more explicitly visual terms:

> If I can't follow, if it's a rat's nest of piping and plumbing and wires and cables, well then I won't be able to figure out where this cable came from, and for that matter, what's on the other end of it. And then it's dangerous ... I don't have to have a tag on every single stainless steel line ... but it shouldn't be untraceable ... if twenty lines penetrate a wall and then I have to find out on the other side of the wall where they went, that starts to make it harder.[31]

This comment lays out a view of the proper ordering of laboratory space that seemed to be an implicit part of many of the practices and interactions I observed in the Plasma Lab. The concept of traceability, as described here, is fundamentally about being able to follow connections in a system – to know the status of system components and trace the influences they may have on one another. This depends on a system displaying both visual and logical order. As will be described below in more detail, traceability is designed into experimental systems in a number of ways – by ensuring that components are well enough separated to prevent unexpected electrical interactions and by ensuring that connections between components are clearly visible, for example.

In Douglas's work, our concepts of order, especially as they are implemented through ritual, are central to knowledge and creativity, because they enable us to select and order experience in a meaningful way (Douglas, 1966: 62-65). Traceability, like other systems of order in scientific work, has epistemic significance because it enables researchers to construct reliable knowledge about system status and about the likely effects of their actions in the laboratory. This knowledge makes it possible to work safely and productively in the laboratory. It may also be important if scientists and technicians need to make credible claims about the proper functioning of laboratory equipment to a wider scientific audience. Under certain circumstances – for example, where the ‘experimenter’s regress’ comes into play – such claims could be crucial to establishing the validity of experimental results.[32] Here, however, I focus on the relevance of traceability to the more practical epistemology of laboratory work, rather than looking at the broader epistemic structure of science. In practice, as the next section shows, creating a well-structured, safe work environment can be a constant struggle, in which an ideal state of order can only be approximated. This is part of the reason why neither laboratory safety nor the process of scientific investigation itself can simply be reduced to a fixed set of rules or ordering principles.

Sources of Uncertainty

Douglas (1966: 122) notes that it is not uncommon for systems of order to encompass certain conflicts or contradictions such that ‘at certain points the system seems to be at war with itself’. This seems to be the case with pulsed power systems. By their very nature, these systems come into conflict with the ideal of traceability at nearly every turn. The main problem is that electricity, at the high voltages found in pulsed power systems, does not always follow the pathways or respect the boundaries put in place by system designers. Instead, it becomes relatively easy for current to strike out on its own by arcing across nominally insulating materials like plastic and air.

Arcing behavior directly challenges the ideal of traceability in two ways. First, it undermines logical order because it is very unpredictable, resulting in unexpected electrical connections between components. Second, it undermines visual order because these unexpected connections are not tied to any previously visible pathways. There are ways of limiting arcing behavior, described below, but researchers emphasized that the performance requirements of pulsed power systems place severe constraints on their ability to deal with this problem. As one scientist explained, ‘the voltages are too high, the spacings are too small, the currents are too high … you just can’t match your required performance and put in a lot of engineering safety factor … the performance will degrade too much’.[33]

Arcing, or ‘breakdown’ of electrical insulators, is a complex and relatively poorly-understood process. The most unpredictable form of this phenomenon is ‘surface-aided breakdown’, which occurs when an arc forms along the surface of an insulating material between electrical components. The risk of such an arc forming can be minimized by lengthening the surface path between charged components. It is for this reason that parts of a pulsed power machine are sometimes draped with translucent plastic: frequently, instead of separating components with a single standard insulator, researchers will separate them with layers of Mylar sheeting. The idea is that any arc will have to traverse both sides of a sheet – a distance of a couple of meters – to get from one component to the other. By using multiple layers – twenty or so – researchers try to ensure that an arc that might find its way through a pinpoint flaw in a single piece of plastic will have to travel around all the other layers. The plastic sheets implement the ideal of traceability by blocking the formation of unpredictable and invisible electrical connections, and thus reinforce the expected boundaries between system elements.

It does not require as much effort to prevent arcs from passing directly through open air and other insulating materials instead of following surfaces, but they are still unpredictable and can cause spectacular system failures. The arcs themselves can be explosive, generating a blinding flash and shock wave that can blow system components apart, creating shrapnel or even flying particles of molten metal. On one occasion I was shown an inch-thick steel plate from a pulsed power machine that operated submerged in oil. The arc had imprinted a fist-sized bulge on the plate – a relatively minor incident, I was told.

Arcs can damage pulsed power systems in a number of other ways, as well. They can cause electrical short circuits that send unexpected surges of current through a system. These can cause serious damage to system components; for example, the magnetic fields generated can rip metal circuit elements from their bolts. Individual components, such as capacitors, can fail suddenly and explosively, just because they are pushed to their limits.

Arcing behavior is one of the few areas in pulsed power where scientists and technicians see system performance as directly connected to standards of order in the form of cleanliness. Surface arcs can be triggered by the tiniest surface flaw or minute speck of dirt. The arc in the oil-insulated machine mentioned above was presumed to be caused by contamination that had settled out of the oil. And if small particles get stuck between layers of plastic, they can create the kind of pinpoint flaws that arcs tend to get through. Researchers try to address these problems by emphasizing cleanliness during certain stages of system assembly, such as when putting down layers of plastic sheet. But in general cleanliness is not treated as an overriding concern, because it’s so hard to tell when dirt will turn out to be a problem – most of the time it doesn’t seem to matter, yet sometimes arcs are attributed to tiny bits of unseen contamination. After a certain point, contamination is treated as an irreducible source of uncertainty, and systems are simply designed to be as tolerant of it as possible.

There can be great uncertainty about the state of a system in the aftermath of an unexpected failure, whether caused by an arc or some other malfunction. A problem might be signaled by a flash and a bang and an automatic system shutdown, but it may not initially be obvious where it occurred. People emphasized that unless and until an investigation produces a conclusive result, doubt remains about whether the capacitors in the system are still charged or not. Because failures are so common – and sometimes are not so spectacular – experienced pulsed power workers make a point of being very cautious around capacitor banks. Ambiguity and anomaly are accepted features of this work environment, but they are not cleanly assimilated into the material order of the laboratory. Instead, their continual visibility reinforces the idea that pulsed power work is inherently dangerous.

People told dramatic stories about the danger inherent in the ambiguity following system failures. One story was about a case in which researchers were testing a system with an improvised piece of copper tubing in place of the experimental apparatus that would complete the circuit in the finished system. The tubing broke loose when current was pulsed through the system. While the other scientists and technicians were trying to establish the cause of the failure, one very inexperienced technician wandered off and pointed at the broken piece of tubing, identifying it as the cause of the problem. As he did so, an arc jumped from the apparatus to his finger, sending a surge of electricity through his body to ground, nearly killing him. He was rushed to the emergency room. (A slightly more experienced lab worker might have known better – one of the first pieces of advice I got when I came to the Plasma Lab was to keep my hands in my pockets around electrical equipment). It turned out that one of the capacitor banks – mounted on top of a metal plate some ten feet from the floor – was still charged, with no connection remaining to ground it. As the story was told to me, after tense, careful deliberation, in the end the researchers had to take a long piece of braided copper cable, attach one end to a grounded connection, tie the other end to 'basically a rock', and throw the rock up onto the capacitor bank, where the cable shorted the bank to ground.[34]

Designing For Traceability

In a perfectly well-ordered pulsed power system, the flow of electricity would be reliably traceable, and an experienced person would avoid danger simply by staying away from known charged parts. But anomalies and ambiguities in system performance are endemic to pulsed power work, and constantly threaten to cause the ideal of traceability to break down in practice. In *Purity and Danger*, Douglas describes a number of different strategies cultures use either to assimilate or expel anomalies from systems of order.

Pulsed power researchers use two main strategies to deal with dangerous uncertainties. First, they work to extend and reinforce the ideal of traceability through system design and safety procedures, forcing uncertainties out of the system. Alternatively, they sometimes choose to accept that traceability cannot be perfectly maintained under all circumstances, and instead put firm boundaries in place to isolate the system from human contact under those circumstances.[35]

In facilities like the Plasma Lab, equipment is actually only charged for a brief period of time before and during each experimental run, or 'shot'.[36] Most of the time, equipment is grounded and power is turned off, and people work freely throughout the laboratory space. In this state, uncertainty about system safety is systematically eliminated by the use of a 'safing' system that reinforces traceability. The term 'safing' is an active verb form of the adjective 'safe' – one can also 'safe' a system or verify that it has been 'safed', for example. Safing involves turning off all high-voltage power supplies and positively connecting all system components to ground. Pulsed power systems usually have mechanized safing systems that do this automatically, but they are supplemented by manual procedures for the sake of redundancy. The basic tools of the manual safing process are called 'shorting sticks'. These are brightly colored wood or fiberglass poles, about the size of a broom handle, with a metal hook on one end that is connected via a cable, through a resistor, to ground. Each major piece of equipment has its own dedicated shorting hook. The resistor – often a large tub of water – provides a 'soft short' that enables equipment to discharge relatively slowly, minimizing the risk of arcing between the hook and any charged equipment.

The manual safing system also emphasizes the visual aspect of traceability. One of the explicitly articulated functions of safing is to structure the laboratory environment so that scientists and technicians can visually verify the grounded status of every piece of equipment. I was told that the brightly-colored shorting sticks are designed to be noticeable, so that a stick out of place would immediately stand out to those familiar with the laboratory. Furthermore, the cables that connect the shorting sticks to ground are deliberately purchased with transparent plastic insulation, just so the integrity of the metal part of the cable can be easily verified.

System designers also try to have the sticks connect as directly as possible to possible reservoirs of electrical charge, so the connections will be more robust and more easily traceable:

> The philosophy is to make sure that your manual system will fully dissipate a fully-charged system safely, regardless of what connections may or may not have been blown off. And so … you want to have your manual system address the capacitors as directly as possible. You don't want to be shorting them out over here assuming some connections are in place.[37]

This 'philosophy' came into play during the design of the safing system for the Plasma Lab equipment when a dispute broke out among the researchers about whether a particular capacitor bank required one or two shorting hooks. One technician argued that the circuit would always keep the two main parts of the bank's chassis at the same electrical potential, so only one hook was required. However, the bank ultimately got two hooks, because most of the technicians and scientists were worried about the lack of a verifiable electrical connection between the two parts – the fact that 'you could not actually see a physical connection'.[38]

When the system is in its charged state, by contrast, traceability becomes more problematic, due to the many uncertainties discussed previously. In this state, the idea of removing ambiguity through intensive application of the principle of traceability is put aside in favor of the alternative strategy of containing the area of uncertainty. Researchers choose to simply assume that the system is in such a dangerous state that it is unsafe for humans to be anywhere near it. Safety is maintained by walling off the area of ambiguity – quite literally – with a 12-foot-tall metal and plywood 'blast wall' that surrounds the entire pulsed power system to prevent human access and contain any flying debris. This wall has doors in it that provide access to the experimental area when the system is not charged. These doors are closed while the system is charged, and are equipped with safety interlocks that automatically safe the system if a door is opened. This physical mechanism ensures that human presence in the experimental area and a charged pulsed power system are mutually exclusive.

Ritual and Traceability

Douglas and others have noted that ritual plays a key role in defining and enacting a culture's ideas about order and pollution. The primary role of ritual is to resolve ambiguity by reinforcing categories and the boundaries between them. Rituals need not be elaborate ceremonies; they can also be relatively mundane routines that serve to structure our everyday reality. Ritual in this mundane sense, even where it is grounded in scientific principles, can still carry important symbolic meanings, according to Douglas (1966: 68-69). This approach to understanding ritual has been important in the study of science and the professions because it provides a pathway toward understanding the possible connections between technical work and normative order.

Pearl Katz's (1981) anthropological study of antisepsis procedures in surgery is a good example of such an analysis. She argues that 'scrubbing' procedures, draping of patients, and the elaborate rules about how to move and what can be touched serve not only to make things sterile, but also to establish clear symbolic boundaries between sterile and non-sterile. By reducing ambiguity in the environment, these boundaries enable doctors and nurses to move more freely and work more efficiently. Others have gone further with this type of analysis. Stefan Hirschauer (1991) argues that antisepsis and other pre-surgical procedures serve to distance physicians from the everyday world and from their patients as persons, so that they may cut into patient's bodies without the feelings of shame or guilt this might otherwise cause.[39] For present purposes, I focus, as Katz does, primarily on how rituals structure the environment in ways that enable the exercise of technical expertise, although in the end the rituals in question also appear to carry more abstract symbolic significance of the sort that Hirschauer examines.

Ritual tends to play an especially strong role during transitions between established states of order, when relationships are ambiguous and the situation is therefore potentially dangerous (Douglas, 1966: 96). I have described two acceptable states of order within pulsed power culture: one where a system is uncharged and safed, and another where a system is charged and enclosed by a barrier that prevents access. The transitions between these states are governed by rituals in the form of safety procedures.

One procedure manages the transition from an uncharged to a charged state.[40] Before the blast wall doors are closed in preparation for a shot, rotating emergency lights are turned on. A designated system operator then searches the experimental area for people. This person has to press 'sweep buttons' in several locations to verify that they have checked the area and it is unoccupied. The sweep buttons must be pressed and the door closed within a specified time period or the whole procedure must be started again. Immediately before a shot, warning horns sound to alert anyone missed in the sweep, and announcements that charging will commence are broadcast over the public address system. If someone were to be trapped in the danger zone, they could press one of a number of 'scram' buttons that immediately safe the experiment.[41] Experimental operations are carried out remotely from a control room outside the blast wall.

The reverse transition – moving from a charged to a verified uncharged state – is accomplished by activating safing systems, both automatic and manual. The manual safing system is put into place following a carefully planned safing procedure. At the Plasma Lab, this procedure can only be carried out by scientists and technicians who have been trained as ‘safing operators’. The safing operators are typically among the more experienced and technically competent scientists and technicians. After a shot has been fired, two safing operators open the blast wall door and enter the experimental enclosure. One person performs the procedure and the other serves as a safety watch and backup. They proceed slowly and deliberately to the nearest shorting stick, which will often be sitting on the floor at a safe distance from the equipment it attaches to. Because of its length and the cable that attaches it to ground, a shorting stick can be rather awkward to handle. The lead safing operator very carefully picks up the stick, grasping it well away from the hook, and carefully maneuvers the hook to its designated resting place, ensuring that that portion of the system is grounded. The team then continues across the room, picking up each shorting stick in turn and hooking it onto its corresponding component, following a predetermined sequence that prevents them from walking to close to any piece of equipment until they have manually grounded it. The other lab personnel must wait outside the door to the experimental area until the procedure is complete.

Although the most obvious purpose of the safing procedure described above is to put a system of traceability into place, it can also be understood as a vehicle for demonstrating the appropriate norms of interaction between people and equipment in the Plasma Lab. Watching the procedure enacted is like watching a morality play in which the actors, through gesture and attitude, very literally demonstrate the concept of ‘ultimate respect’ toward pulsed power equipment.[42] The pre-shot safety procedure, too, helps define the relationship between workers and pulsed power equipment by clearly drawing spatial and temporal boundaries around a set of circumstances in which any direct interaction between the two must be strictly forbidden. These procedures, viewed as mundane rituals, not only help manage transitions betweens states of order, but also appear to play a crucial role in making standards of order and safety visible to the entire laboratory community. Because of this, they are arguably central to the production and reproduction of the laboratory culture.

Safety and Social Order

The previous section focused on one aspect of the connection between pollution and order in laboratory safety: the organization of the material space of the laboratory to maintain traceability and remove danger. However, this material ordering turned out to play a role in setting up certain norms for human conduct, particularly for the interaction between humans and machines. Indeed, traceability itself is a norm of human conduct, since it specifies standards for how people should approach the design and operation of pulsed power systems. In this section, I move away from the technically-mediated interaction between humans and the material world, and instead focus on the norms of interaction between members of the pulsed power community. The emphasis here is not on the broad normative structures of science, but rather on the norms that people use to guide and evaluate their daily work in the laboratory, particularly in connection to safety issues. The study of such locally meaningful norms can help us understand the connections between technically-mediated norms like traceability and the broader moral constitution of the scientific community.

Douglas argues that pollution beliefs can be used as analogies for an ideal social order, or as means to enforce that order. Here, I describe how ideas about safety and danger are used to reinforce two key norms of conduct in the Plasma Lab: caring and competence. While safety is not the focus of either norm, the language of safety and danger is used to make them seem necessary. Also, unlike some of the social rules discussed by Douglas, these norms are not enforced in a direct way. Instead, they seem to function more as standards by which people in the group judge the moral and technical worth of themselves and their colleagues. In this sense, they implement a certain vision of social order. In the end, this vision of social order is intimately related to notions of material order, because one of the crucial things that people care about, and try to be competent at, is maintaining traceability in the laboratory.

Caring

When I discussed safety with Plasma Lab personnel, the words ‘caring’ and ‘careful’ came up repeatedly. There appeared to be two distinct but closely related meanings attached to the words. First, ‘caring’ could describe a general sense of taking pride in one’s work and paying attention to detail. In this usage, ‘caring’ carries a similar meaning to ‘being careful’. For example, one scientist talked about

> that whole caring business, caring about what you’re doing, in all levels, I mean including that it’s being done safely and neatly and/or … quickly and efficiently and all those good words. They’re not exclusive. They go together with somebody that’s paying attention. [If somebody is] not paying attention, they’re listening to

> the radio, they’re doing something, they’re thinking about something else, and then they’re not safe, you know.[43]

Rituals like safing appeared to play a key role in delineating exactly what the concept of ‘being careful’ entailed in a practical sense. The systematic planning of these procedures, along with the attitudes of seriousness and concentration displayed in their execution, were a highly visible model for working safely in the Plasma Lab. Caring in this sense was connected to standards of material order because it often involved showing proper respect for the boundaries that define safety in pulsed power systems.

In other circumstances, ‘caring’ took on a meaning that was closer to ‘caring for’ others – making sure other people didn’t put themselves in danger, or simply caring for the laboratory space out of concern for other people’s well-being as well as one’s own. This sense of ‘caring’ was directly linked with the idea of maintaining traceability in the material environment of the laboratory. For example, one technician described a situation that had occurred recently when an air hose was disconnected. This was a potential danger because if someone turned the air back on without knowing that the hose was disconnected, the escaping air could cause the hose to whip across the room. The technician explained: ‘I could have just left the hose there and not even said anything and not cared, so that’s down to the ground level person, if you care, then you’ll ask somebody and you’ll find out, if you don’t care, you just leave it’.[44] Leaving an air hose disconnected removes an expected relationship between system components in a way that might not be immediately visible to someone turning on the air supply, and might directly hurt somebody. In this context, maintaining traceability becomes a moral obligation to co-workers as well as a technical norm.

The concept of caring often entered into laboratory workers’ evaluations of each other as co-workers, particularly around issues of safety and risk-taking. In some cases, the two senses of the word – ‘being careful’ and ‘caring for’ – seemed to reflect a distinction between risk-taking as an individual choice or a group problem. For example, one scientist described the circumstance where ‘you’re looking through a hole in a box, and there are cables coming in there with high voltage’. His assessment was that this is an acceptable situation, ‘you just have to be careful’.[45] A postdoc brought up another situation in which he felt that a colleague was putting himself at risk by not being careful enough. In this case, the postdoc felt a responsibility to intervene to protect his co-worker from harming himself: ‘for example … diagnosing … an electrical box when it’s plugged in, you know, sticking your hand in there … I have to actually tell him not to do it, or unplug it for him’. Here, the postdoc felt he was forced to take action by his colleague’s failure to be sufficiently careful. He therefore perceived an unequal distribution of the burden of ‘caring for’, which he expressed as ‘I always feel like I end up being the enforcer, you know, the guy that always says … you gotta do this safer’. His general perception of his situation was that ‘I mean, I actually care, but some people don’t care’.[46]

This kind of complaint was not uncommon. Others also mentioned playing the role of enforcer or described themselves as more careful than others – even people who were themselves described as careless by others. These assessments of other people's levels of caring were part of how people evaluated their interactions with co-workers, and part of how they identified themselves as being good colleagues. The norm of caring therefore served as a common standard by which all Plasma Lab personnel established their membership in, and commitment to the research group. At the same time, it was a source of internal conflict and a resource for pursuing and resolving disagreements within the group. In both of these capacities, the concept of caring seemed to be a key element in defining group culture and individual identity in the Plasma Lab.

Competence

Competence was another key norm that played a role in many interactions in and around the Plasma Lab. Scientists and technicians expressed slightly different perspectives on what competence entailed, but generally agreed that it was derived from experience with pulsed power. Technicians focused mainly on skills and knowledge gained from hands-on experience. For example, one technician spoke of 'the technical leadership of people that know things like … I've tried it that [way] and that way doesn't work … a lead tech type person or something that had just a lot of accumulated experience'.[47]

Scientists placed more value on formal knowledge and education, but still with a characteristic emphasis on experience. One scientist described where his knowledge about designing pulsed power systems came from:

> You have computer models for your circuits, you have books and diagrams for … your hardware, and you look up papers for what switching mechanism you might want to use. Maybe it's one you've used in the past … maybe it's one that your buddy at [a university] used in the past, whatever. So we don't just start from gee, what's voltage and what's current … we've been doing this for twenty years, literally, as graduate students also.[48]

Although these statements clearly place competence in a broader context than safety, the need to gain knowledge from experience seemed to take on particular significance in relation to safety. Lack of experience was a safety concern particularly in relation to students and other laboratory personnel new to the pulsed power laboratory. Another scientist discussed his concerns about training students:

> One of the things that I find that's scary [is that] either through experience or some natural instinct to start with … I can go into a pulsed power laboratory and know full well and understand that mistakes would be deadly. Students don't know that … they don't have the experience … I mean you tell them this capacitor bank holds ten kilojoules, that means nothing to them … many of them just don't have that safety state of mind because they just have no clue.[49]

This point was sometimes reiterated in relation to the case described above in which a new technician was nearly electrocuted while pointing at a charged capacitor bank.

Accounts of this incident were used not only to emphasize the uncertainty inherent in pulsed power systems, but also to make the point that only people who have experience with pulsed power systems can adequately understand the dangers. More specifically, the story conveyed the urgency of keeping inexperienced workers under close supervision, lest their safety instincts turn out to be poor.

The emphasis on hands-on experience as a prerequisite to competence had an interesting effect on status hierarchies in the Plasma Lab. It has been observed in other laboratory settings that the scientific community seems to place a greater value on purely intellectual work than on work involving manual skill. This valuation of 'head' over 'hand' is reflected in various status hierarchies, such as the greater esteem generally granted to theoreticians over experimentalists, or the supervisory control scientists have over the work of laboratory technicians.[50] But the effects of this norm can be muted, to some extent, by the existence of competing norms that place more emphasis on skill and experience. Certainly Plasma Lab technicians were not going to conferences, publishing papers, or receiving research funding directly. Scientists did not necessarily go out of their way to single out the contributions or superior practical knowledge of technicians. But in interactions with scientists inside the laboratory, particularly around safety issues, technicians seemed to participate as equals. This may be because workplace safety discussions often had little to do with specialized physics knowledge, and more to do with standard practices and rules of thumb in pulsed power work – and on those topics, technicians had the credibility to speak with as much or more authority than scientists by virtue of their experience. This authority was also enacted and reinforced through the lead role typically taken by technicians in prominent safety routines, such as safing.

Competence was also the main criterion invoked to draw distinctions between the Plasma Lab group and outsiders. In this sense, it was used to maintain order within the laboratory community by policing its boundaries and denying legitimate membership in the community to problematic individuals. Lab personnel were often harshly critical of outsiders who were not familiar with pulsed power work yet presumed to get involved in laboratory safety. Institutional safety personnel bore the brunt of this antagonism, but it was also directed at many managers and even colleagues outside of the Plasma Lab. Although these individuals might be seen as caring about safety, they were faulted for not having sufficient experience, and therefore technical competence, in a pulsed power setting. The emphasis on skill and experience in the safety context seemed to be one basis for drawing firm social boundaries between the Plasma Lab team and the outside world and for maintaining a sense of solidarity among team members.[51]

While the demarcation between competent insiders and incompetent outsiders was a frequent theme of conversation at the Plasma Lab, in practice the boundary was not always clear. This was especially problematic in the context of getting the laboratory's safety documentation written and approved, a process which seemed to require constant assessment and renegotiation of the insider – outsider demarcation. In particular, it provided some interesting insights into how the norm of competence was deployed to reassert group boundaries in situations where they were potentially threatened by outsiders.

At LANL, the key safety document for a facility like the Plasma Lab is its Hazard Control Plan (HCP).[52] An HCP describes the laboratory, its equipment, all significant safety and environmental hazards, and how these risks will be mitigated. HCPs were introduced as part of an effort to implement a very specific safety philosophy, one that emphasizes worker involvement and tailoring of safety measures to specific work situations. In keeping with this philosophy, HCPs are written and agreed to by laboratory personnel. However, HCPs also must be approved by the relevant line manager, and depending on the situation, by one or more peer reviewers or safety personnel. Writing these documents therefore requires a great deal of interaction between lab personnel and these outside parties. When I was studying the Plasma Lab, writing the HCP document and getting it approved was one of the main avenues of interaction over safety issues, both among laboratory personnel and between laboratory insiders and outsiders. Like safing, writing an HCP is a kind of ritual that both enables laboratory work and serves to delineate a certain set of normative social relationships. However, unlike safing, it is a bureaucratically imposed process, and a potentially problematic one for researchers, because it requires them to explain and justify their expertise to outsiders.[53]

Although the process of writing and getting approval for the Plasma Lab HCP was not unusually eventful, some minor controversies did emerge. These controversies all stemmed primarily from the input of one of the reviewers, who was someone with extensive experience in pulsed power. For example, the dispute described above over whether a particular capacitor bank required one or two shorting sticks was originally instigated by this reviewer, who thought it should have two. The reviewer also questioned a decision by the researchers to replace some of the resistors that came mounted on the shorting sticks with copper connectors. The researchers were concerned that the resistors might heat up or explode if the full energy of a capacitor bank were accidentally discharged through them. The reviewer didn't think this would happen, and thought it would be better not to modify the sticks.

This reviewer was a problematic figure, not because he was particularly critical, but rather because he did not easily fit into the social order of the laboratory. He was seen as both an experienced pulsed power expert and as an outsider operating in an institutional role. As a result, people typically expressed respect for his expertise before discussing their disagreements with him. He was described by one of the researchers as the 'one guy that really was fully knowledgeable of the more dangerous parts' of the experiment.[54] The researchers interacted with him on a friendly basis and worked to accommodate many of his concerns. However, in their conversations with each other and with me, they also found ways to rhetorically reassert the boundaries of the group in relation to the reviewer. In particular, the norm of competence based on experience was subtly invoked to question the credibility of his concerns and reinforce distinctions between insiders and outsiders.

For example, one technician, expressing some frustration with the reviewer, described him as acting ‘like he’d been to a class, and he was kind of exercising his skills that he’d learned in the class as far as … what the new safety position is as far as … experiments are concerned’.[55] This technician questions the competence of the reviewer by suggesting that his criticisms are based on purely academic knowledge not derived from his pulsed power experience. Similarly, one of the scientists described the reviewer as being overly picky. He also pointed out that the reviewer, like most people who have time to review HCPs, was not currently busy with technical work, and as a result felt he had to have an impact on the HCP.[56] Again, the subtext is that the reviewer’s concerns are being driven by something other than his experience and active engagement in pulsed power work. Both of these remarks seem to be attempts to shift the identity of the reviewer in a way that emphasizes his bureaucratic role and de-emphasizes his insider competence, making him a less threatening figure. This allowed the researchers to work to resolve the reviewer’s concerns while preserving their own sense of unique technical competence. In this situation, a norm such as competence does not function as a fixed criterion for determining who is a group insider, but rather as a tool for rhetorically asserting group boundaries in order to define individual identities in relation to technical problems.

Social Order and Material Order

This examination of the norms of caring and competence shows how material order and social order reinforce one another in the Plasma Lab. The language of danger is used to argue that people should be careful and should care about colleagues and the laboratory space, and that competence derived from experience is a proper indicator of technical authority. However, notions of danger are frequently invoked in relation to specific standards of material order, such as traceability, which are embedded in technical practice. As a result, successfully interpreting and acting on the norms of caring and competence, as they are understood in the Plasma Lab, can depend on familiarity with technical aspects of pulsed power work.

This connection between material and social order may explain some of the strained relationships between the Plasma Lab researchers and outsiders, such as safety personnel. At one level, researchers may cite outsiders' lack of technical expertise in pulsed power as a reason for questioning their ability to contribute to safety decisions. But on another level, people who lack this kind of insider expertise can also be seen as not fully morally committed to safety or to pulsed power work more generally. This perceived lack of moral commitment may make their participation in the definition of order and danger in the laboratory even more problematic than would be implied by their lack of pulsed power expertise alone. This can also work in the other direction, as in the interaction with the outsider reviewer. In that case, comments about the reviewer's normative commitments called into question the credibility of his technical judgments, even though he was to some degree considered a pulsed power insider.

The identity of the Plasma Lab as an independent and unique entity within a larger institution is doubly reinforced through this connection between material and social order. The Plasma Lab community, like many research groups at LANL and other scientific institutions, is most visibly and formally defined by its technical expertise in a particular research area. But because standards of technical practice are embedded in a larger normative realm, it is not surprising that these technical communities turn out to be moral communities as well. This dual character reinforces the identity and boundaries of these communities, and sets the stage for their resistance to the imposition of bureaucratic rules, including safety rules.

Conclusions

Safety Culture

The laboratory culture described in this article is one in which safety is a central organizing concept that structures everything from the design and spatial arrangement of equipment to behavioral norms and group identity. Examining such a culture is useful because it demonstrates the wide range of impacts safety can have on scientific work. Future work on laboratory safety might put these findings in context by examining a range of variations in perceived risk and work culture. Consider one contrasting case: a bioscience research facility studied as part of this project. Work at that facility did not involve living infectious organisms and was considered by researchers to be relatively low risk. The most significant risk was seen as coming from exposure to poisonous or cancer-causing chemicals. Since these chemicals do not necessarily leave a visible trace, there was little emphasis on the visual order of laboratory space as a safety issue. Instead, risk was addressed through routine cleaning and decontamination procedures. Safety played a relatively minor role in the technical and moral constitution of research work.

This different orientation toward safety seemed to be linked to organizational and cultural differences between the bioscience and plasma physics communities. In the bioscience facility, people typically worked individually on a set of related tasks, rather than solving problems collectively. There was greater role differentiation between scientists, postdocs, and technicians.[57] Compared to the Plasma Lab, there appeared to be a more individualistic culture that did not place as much emphasis on maintaining group solidarity.[58] This culture seemed to be more open to outside intervention on issues like safety, perhaps because such intervention did not threaten to undermine an existing strong sense of group identity like that found in the Plasma Lab. These differences suggest that levels of concern or conflict regarding safety are correlated with other technical and social features of scientific work.[59]

The full complexity of the relationship between safety and culture could also be studied by comparing different high-risk work environments. Researchers studying 'High Reliability Organizations' have identified cultural characteristics of such organizations that seem broadly similar to the safety culture in pulsed power.[60] Yet there are many examples of work cultures in which risks are perceived to be significant, but risk-taking is tolerated or even, in some cases, encouraged. The French nuclear engineers and technicians described by Gabrielle Hecht (1998: 178-179), for example, viewed some forms of risk-taking as heroic, a characteristic they seem to have shared with their earlier counterparts at Los Alamos. The existence of such different work cultures implies that definitions of risk and safety, and the norms of behavior that are associated with these concepts, vary widely across time and space. A broader, cross-disciplinary and cross-cultural study of safety practices might further illuminate the influences on local safety cultures of a variety of factors, including different scientific methods, techniques, and research styles; group and institutional structures; national cultures; social hierarchies; and historical, social and political circumstances.

Order, Pollution, and Scientific Culture

This study of pulsed power safety shows how the technical, normative, and social orders of laboratory work can overlap and influence one another. The pulsed power community demonstrates an overriding commitment to safety occasioned by its highly technical knowledge of pulsed power equipment and the danger it poses. This commitment to safety is expressed at a technical level through the concept of traceability in the design of systems. It is further enacted and reinforced in the community through the use of safety procedures that also serve ritual functions. Traceability also plays a role in defining more general norms of conduct and interaction within the group. This moral context ultimately shapes the social organization of the group and its relationship to its institutional and social setting. By examining these different levels of order in laboratory work, we gain a greater appreciation for the overall texture of laboratory culture.

Research on cultural conceptions of pollution, by Mary Douglas and others, provides a key set of resources for understanding the connections between these different levels of order in a community. This work makes it possible to understand how the ideals of material order we express through everyday practices like building and cleaning can be connected to grander notions of moral and social order. More specifically, it shows how the structure of our knowledge about the material world may be connected to our beliefs about right behavior.

With some notable exceptions, laboratory studies have focused mainly on the practices by which scientists impose order on the material world in order to produce new scientific knowledge. This perspective has been valuable because it shows how scientific epistemology is grounded in the routines of scientific practice. It has also played an important role in extending the scope of the sociology of science beyond the study of broad normative and institutional structures, by showing that scientific culture can be understood from an ethnographer's perspective through close examination of the scientific workplace.

Like other laboratory studies, this paper examines the techniques one group of scientists uses to order the material environment of their laboratory. But I also show how the concepts that underpin this material ordering influence and interact with the behavioral norms and social structure of the laboratory work group. This demonstrates that the normative and institutional structures of science can be addressed in the context of a laboratory study, and that detailed ethnographic studies of scientific work can, and should, be used to address these classic topics in the sociology of science from a new perspective.

This study also shows that where safety is important, how it is conceptualized and enacted will be fundamentally entangled with communal ways of knowing, technical practices, and modes of normative and bureaucratic control. Because safety cuts across these aspects of scientific culture, it provides an opportunity to understand how ideals of material and social order are enacted through specific practices, routines, and rituals in the course of technical work. From this perspective, the laboratory can be seen as playing a foundational role not only in the generation of scientific knowledge, but also in the creation and reproduction of the culture of science more generally.

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Notes

I would like to thank Robert Benjamin, Christopher Henke, Andrew Koehler, Laura McNamara, Cyrus Mody, Steven Shapin, Susan Silbey, Greg Wilson, Hugh Gusterson, and the anonymous reviewers for their helpful comments on previous drafts and presentations of this work. Thanks also to everyone at the Plasma Lab and to the LANL managers who have supported this project.

[1] Laboratory studies that established this line of argument include Collins (1974), Knorr Cetina (1981), Lynch (1985), and Latour & Woolgar (1986).

[2] As Stephen Hilgartner (1992: 41) argues in relation to the social problems literature, ‘we cannot assume that the process of linking an object to a putative harm is independent of the process that defines the object as an *object*’.

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[3] On the early history of the U.S. work safety movement, see Aldrich (1997). U.S. government regulation of workplace safety expanded significantly with the passage of the Occupational Safety and Health Act (OSHA) in 1970 (Mintz, 1984).

[4] The expansion of safety efforts to different types of work possibly has its origins in the movement in the corporate world toward 'continuous improvement' in business processes. Recent approaches to occupational safety have emphasized the modification of individual behavior and organizational culture, rather than the work environment, as holding the greatest potential for further improvement in safety. They have also suggested that significant safety improvements can be made even in low-risk work environments. For a discussion of the enforcement of safety regulations in an academic setting, see Mody (2001: 21-23).

[5] Consultants in the area of 'behavioral safety', a psychological approach based on behaviorism, talk generally about cultural change as a goal of their work. See Krause, Hidley & Hodson (1990), for example; Geller (1998) is more direct, using the term 'Total Safety Culture' to describe the desired outcome of his approach. There is another body of literature that uses the term 'safety culture', which is based more on work in organizational change and on developments in the nuclear regulatory arena. See International Nuclear Safety Advisory Group (1991), Cooper (1998); and Glendon & Stanton (2000).

[6] For a similar cultural perspective on safety in a non-scientific setting, see Gherardi & Nicolini (2000; 2002).

[7] Douglas also notes that ambiguity is not necessarily seen as something that must simply be eliminated. It prompts efforts to impose order in part because it can also be a potent

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source of power (see also Turner, 1969: 108-11.) The expert authority of scientists, for example, seems to rest, in part, on the ability to order and control a potentially disorderly natural world.

[8] Mody (2001) discusses safety in the context of a larger study of the role of contamination in a materials science laboratory, grounded in Douglas' work. Mody argues that cleanliness 'is a kind of Foucaultian discourse allowing for surveillance and discipline' and notes that tension between laboratory workers and safety personnel often revolves around conflicting definitions of cleanliness. The suggestion is that different ideas about safety are essentially alternate visions of moral order. Galison (1997: 352-62) finds similarly clashing viewpoints in the early 1960s between high-energy physicists and U.S. Atomic Energy Commission (AEC) regulators over safety in accelerator facilities. In the wake of a deadly hydrogen-fueled fire at one major research center, AEC regulators were able to decisively impose their view of laboratory life, which emphasized bureaucratic rules and management control, over the physicists' desire for a more flexible and informal work environment. This led to significant changes in the social organization of the high-energy physics workplace, with far-reaching consequences for the future of the field and experimental physics in general. Finally, Traweek (1988), an anthropological study of the Stanford Linear Accelerator Center (SLAC), discusses the importance of radiation safety concerns in defining the relationship between the Center and nearby communities, expressed symbolically by the Center's 'radiation fence'. On cultures of radiation safety, see also Hecht (1998):163-99.

[9] Susan Silbey (2003) is similarly concerned with the relationship between safety regulation and scientific practice, which she addresses from a broader institutional

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perspective than this paper takes. Her work examines the responses of different departments at a university to a new regime of safety regulation. She argues that certain historical, organizational, and epistemological features of scientific fields account for the departments' differential responses to the new regulatory scheme. See also Silbey & Ewick (2003).

[10] A few excellent ethnographic studies have been done on weapons-related work at U.S. National Laboratories. The most well-know of these is Hugh Gusterson's (1996) study of Lawrence Livermore National Laboratory scientists. On Los Alamos specifically, see Koehler (2001) and McNamara (2001).

[11] A notable demographic feature here is that many of the technicians come from Hispanic communities near Los Alamos, while most of the scientists are not Hispanic and have come to Los Alamos from elsewhere in the United States, following scientific career paths. Both the scientists and the technicians in this laboratory were overwhelmingly male. These facts do not seem immediately relevant to the cultural issues I discuss here, although they would become very important in a larger analysis of LANL culture. Differences of opinion about safety, and differences in safety practices, seemed to depend much more on the role of individuals in the scientific work process – as technicians, scientists, managers, safety personnel, etc. – than on broader social differences.

[12] These capacitor banks are called 'Marx generators'. The capacitors are arranged so they can be charged in parallel to a certain voltage, then discharged into an electrical circuit in series, adding their voltages and generating a large pulse of current. They are named after their inventor, Erwin Marx, and are described in detail in Kuffel & Zaengl (1984: 65-72).

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[13] These numbers are cited in the Plasma Lab's Hazard Control Plan, a safety document; I have deliberately given approximations to maintain the anonymity of the facility.

[14] For an overview of current problems in pulsed power, the wide variety of its applications, and where research is being done, see the recent special pulsed power issue of *IEEE Transactions on Plasma Science*, Vol. 28, No. 5 (October 2000).

[15] The TEA lasers described in Collins (1974) and Collins (1992: 51-78) are smaller pulsed power devices, and this precise problem is central to Collins' discussion of replication. In both cases, the goal is to arrange electrical components to discharge power in a controlled manner without unwanted arcing between components, and the primary challenge is to anticipate the complex and unpredictable behavior of these electrical discharges.

[16] For an overview of electrical hazards relevant to pulsed-power work, see Gordon (1991: 231-236).

[17] Interview, Scientist #2, June 5, 2001. Interviewees are referred to by occupation rather than name to preserve anonymity. Numbers are designations from my notes and refer to the order in which interviews were conducted.

[18] Interview, Scientist #3, June 7, 2001.

[19] With this in mind, note that I was employed by the Environment, Safety and Health Division at LANL at the time I did this research. This made me an insider at LANL, but at the same time threatened to make me very much of an outsider to the researchers I studied, since they tend to view safety personnel as bureaucrats to be avoided wherever possible. To minimize this issue, when I requested access to the Plasma Lab, I emphasized my academic credentials in sociology and my previous experience studying

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and working in laboratories, and my relative ignorance in the safety field. I was allowed to enter the laboratory as a participant, carrying out basic tasks much as an undergraduate student might do. This seemed to be critical for gaining the trust of the people working in the laboratory.

[20] On learning to be a competent member of a safety culture, see Gherardi & Nicolini (2002); on entry into a community of practice more generally, see Lave & Wenger (1991).

[21] On the early history of safety at Los Alamos, see Hacker (1987: 59-83). See also the articles and interviews in Cooper (1995).

[22] Here, I use the term 'traceability' to capture a particular way of attending to laboratory space that I observed in the Plasma Lab. However, this term also comes up in other areas. For example, Javier Lezaun (forthcoming) shows how the idea of 'traceability' has become an important principle in the regulation of Genetically Modified Organisms (GMOs) in the food supply. In that case, 'traceability' refers to the ability to track GMOs and their derivatives through the food production and distribution chain. Although this usage is different than mine in some respects, it suggests that the ability to trace connections between potentially dangerous entities may be a relevant metaphor for order in other contemporary technical and regulatory arenas.

[23] Observed in the field, possibly told by Scientist #2, unknown date.

[24] Interview, Technician #1, March 2001.

[25] For further discussion of how professionals visually structure the environment in order to exercise their expertise, see Goodwin (1994).On the use of environmental features to structure human cognition more generally, see Lave (1988) and Hutchins (1995).

McEvoy (1995) analyzes industrial safety in terms of the interaction between humans and work environments.

[26] The connection between safety and housekeeping is commonly mentioned in industrial safety textbooks. See, for example, Hammer (1989: 188) and Goetsch (1999: 332). On the use of housekeeping as an indicator of safety in companies, see Cooper (1998: 246-47); in high-energy physics laboratories, see Galison (1997: 360).

[27] Interview, Technician #2, June 5, 2001

[28] Interview, Technician #1, March 2001

[29] Interview, Technician #1, March 2001.

[30] Interview, Scientist #2, June 5, 2001.

[31] Interview, Scientist #2, June 5, 2001.

[32] On ‘experimenter’s regress’, see Collins (1992: 79-128). Unfortunately, the present study provides no clear example of such a situation. Another useful way of conceiving of the relationship between knowledge about scientific apparatus and knowledge about the objects of scientific study is Karin Knorr Cetina’s (1999: 55-63) use of Michel Foucault’s concept of ‘care of the self’. Knorr Cetina uses the phrase to describe the work done to construct and maintain knowledge about the behavior of the experimental apparatus in high-energy physics experiments. She argues that this work is a key aspect of experimental practice in the field, ultimately ‘re-entering’ into the physics analysis of experimental results.

[33] Interview, Scientist #3, June 7, 2001.

[34] Interview, Scientist #3, June 7, 2001.

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[35] This is consistent with the argument made in Hilgartner (1992) that risk is commonly eliminated from technological systems either by displacing the entire ‘risk object’ from the system (removing snow from roadways, for example) or by controlling the risk object in a way that keeps the object in the system while displacing the danger it poses (as when we put technical controls in place to prevent the combustion of gasoline in pipelines and gas tanks).

[36] This term was probably adopted from the same term used for nuclear tests and high-explosive experiments at the Laboratory. The connection may have arisen through experimentation with explosives-driven inductive pulsed power devices.

[37] Interview, Scientist #3, June 7, 2001.

[38] Interview, Technician #1, March 2001.

[39] Hirschauer’s paper triggered a debate on whether social explanations of technical practices should stick closely to the ‘form of life’ of the research subjects – in this case, surgeons – or whether more abstract analyses of the symbolism in technical practices can be useful. See Collins (1994a), Hirschauer (1994), Fox (1994), Lynch (1994); and, finally, Collins (1994b). I believe either style of explanation can be valuable, depending on what claims one wants to make, and that the sociology of science should make room for more of the latter type of analysis.

[40] The following descriptions of procedures are derived from my observations and the Plasma Lab Hazard Control Plan.

[41] A term adopted from similar buttons for rapid shutdown of nuclear reactors.

[42] Robert Benjamin suggested this interpretation to me.

[43] Interview, Scientist #2, June 5, 2001.

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[44] Interview, Technician #2, June 5, 2001.

[45] Interview, Scientist #1, March 2001.

[46] Interview, Postdoc, March 2001

[47] Interview, Technician #1, March 2001.

[48] Interview, Scientist #2, June 5, 2001.

[49] Interview, Scientist #3, June 7, 2001.

[50] See Shapin (1994: 378-83); Mukerji (1989: 125-45). On the roles of technicians more generally, see Barley & Bechky (1994), Barley (1996), Henke (2000), Orr (1996), Shapin (1989), Sims (1999); and the contributions to Barley & Orr (1997).

[51] This fits well with the argument made in later work by Douglas and Wildavsky (1982), that groups that are concerned about pollution tend to be relatively internally undifferentiated and to draw sharp boundaries between themselves and the outside world. Rayner (1986) places this insight in organizational context through a fine-grained ethnographic study of radiation safety in hospitals. As I explain below, however, this approach is probably overly simplistic, and furthermore does not attach enough importance to the actual practices through which people construct their knowledge and beliefs about risk. See Shrader-Frechette (1991) for a much more pointed criticism along these lines. Douglas' earlier work is the basis for this argument, but it does not seem to necessarily imply this kind of structural determinism. An alternate explanation for the antagonism between these researchers and safety personnel is suggested in Gouldner (1954: 164). Gouldner argues that group norms can serve the same functions as bureaucratic rules, and that bureaucratic rules seem to be most necessary in situations where strong group norms do not exist. Following this line of reasoning, a group with its

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own strong safety norms may resent the imposition of bureaucratic safety rules because they conflict with existing group norms, or simply because they are functionally redundant. Interestingly, in Gouldner's study safety was one of the areas in which bureaucratic rules were a source of positive interactions between managers and workers.

[52] Hazard Control Plans have been replaced by a new documentation system since this paper was initially submitted, but I continue to use present tense to avoid adding complexity to the language here.

[53] I helped write the Plasma Lab HCP in my capacity as a laboratory worker, and participated in, or heard about, many of the interactions surrounding the document.

[54] Interview, Postdoc, March 2001.

[55] Interview, Technician #1, March 2001.

[56] Interview, Scientist #1, March 2001.

[57] For example, there appeared to be much sharper, more traditional status distinctions between scientists and technicians in the biosciences. Perhaps not coincidentally, the majority of bioscience technicians were female, while pulsed power technicians were overwhelmingly male.

[58] This observation is in line with Karin Knorr Cetina's (1999: 159-240) observation that the individuation of participants is a central feature of molecular biology collaborations, while high-energy physics collaborations tend to operate on communitarian principles. Although the Plasma Lab community is much smaller than the high-energy physics collaborations described by Knorr Cetina, it seems to have a similarly communitarian social organization.

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[59] Silbey (2003) describes some of these correlations and suggests a framework for studying them.

[60] See La Porte (1996), and Weick, Sutcliffe & Obstfeld (1999).

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