NUCLEAR SAFETY:

A (CHARLIE) BROWNIAN NOTION

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ABSTRACT

Both the legitimacy and governance of nuclear power plants are premised on formal calculations (probabilistic risk assessments) proving that major accidents will not happen. The 2011 meltdowns at Fukushima suggests that these calculations are untrustworthy. Yet the assessment process has retained its legitimacy: the 'nuclear renaissance' continues almost unabated, with policymakers invoking the same assessments to rationalize it. This is possible because – as with Three Mile Island and Chernobyl – public accounts of the accident have framed the disaster in ways that 'redeem' the legitimacy of nuclear risk assessment as a practice. This paper looks at how. It outlines four basic 'rites of redemption': narratives by which accounts distance the failure to predict Fukushima from the credibility of nuclear risk calculations writ-large. It critiques each of these narratives in turn, and argues that they serve to occlude a wider truth about complex technological systems, with perverse consequences regarding public policy.

[1] This paper is based on a talk given at the Eleventh Bieleschweig Workshop. Bielefeld, 3-4 August 2011. (Under the title: "Why Do We Trust Nuclear Safety Assessments?") The author would like to thank Chick Perrow; Lynn Eden; Peter Ladkin; Chip Clarke; Benoît Pélopidas; Lori Bystrom; Anne I. Harrinton; Henry Rothstein and Rebecca Slayton for their time, support and advice at different stages of this paper's overlong gestation. All its failings are, as ever, the author's alone. This research was generously funded by the Stanton Foundation.

Those who remember history are condemned to repeat it too. That's a little history joke.
~Michael Herr.

PART ONE: Fukushima Football

Introduction:

In March and April of 2011, the world watched as a series of unfolding reactor failures in Japan gradually escalated in severity, one increment of the 'International Nuclear Event Scale' at a time, until 'Fukushima' reached taxonomic parity with 'Chernobyl' and became a new synonym for technological disaster. The meltdowns and their attendant dramas – evacuations; bankruptcies; health alerts – dominated the headlines for many weeks, and a deluge of detailed analysis poured forth from every media outlet.

Immersed in this discourse of disaster, with its ominous, modernist lexicon of 'millisieverts,' 'zircaloy' and 'suicide squads,' it was tempting to reflect on the hundreds of other nuclear plants around the world, many of them much closer to home. And when British and French officials started advising their nationals to consider evacuating Tokyo[2], it was difficult to avoid wondering if the people of London, Paris or New York might one day be hurrying confused children into cars in the middle of the night, uncertain if they would ever see their homes again.

Nuclear authorities and their experts campaigned hard to assuage such fears by 'educating the public' about nuclear safety in the popular press. But for decades prior to the meltdown, these same authorities had been promising that Japanese reactors were safe. The accident thus posed an important question: how can the assurances of nuclear experts remain credible in the wake of Fukushima?

Serious reactor accidents are incredibly unlikely, or so formal risk calculations routinely demonstrate. In a characteristic declaration to a UK regulator,[3] for instance, Areva asserts that analyses of its new 'EPR' reactor show the likelihood of a 'core damage incident' to be of the order of one incident (per reactor) every 1.6 million years; and, in a separate document, describe the probability of a core-melt as 'infinitesimal' (in Ramana 2011). Similar assessments performed on earlier generation reactors like Fukushima have found the risks to be higher, but

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[2] Advice, it would later emerge, that the Japanese government was itself considering (Quintana 2012; Fackler 2011).

[3] Online: http://www.epr-reactor.co.uk/ssmod/liblocal/docs/V3/Volume%202%20-%20Design%20and%20Safety/2.R%20-%20Probabilistic%20Safety%20Assessment/2.R.1%20-%20Level%201%20Probabilistic%20Safety%20Assessment%20-%20v2.pdf

still nowhere of an order that would justify significant public concern. An oft-cited figure that framed nuclear discussions before 2011, put the likelihood of a severe accident in an operational reactor at 'one in a hundred-thousand years' (eg: Glaser 2011). Yet nuclear accidents happen far more often than formal calculations predict (Ramana 2011); the 2011 meltdowns being just the latest addition to a substantial list of atomic calamities and near-calamities. Even with the relatively tiny number of reactors in operation (around 400 at present) there exists a legacy of major disasters – Windscale; Chernobyl; TMI; now Fukushima.

This legacy, we might imagine, might discredit the pervasive belief that nuclear risks can be calculated with any objective certainty. The implications of this would be immense. Risk calculations frame a wide range of societal decisions about nuclear power. Indeed, many observers argue that they are the sine qua non of most national reactor programs. Clarke (2005), for instance, argues that, historically, US nuclear authorities have publicly legitimised nuclear power by viewing safety through the lens of probability – via Probabilistic Risk Assessment (PRA)[4] – and showing that the extreme hazards of reactor accidents are offset by their extreme improbability (Clarke 2005: 50). [5]

If history is any guide, however, then Fukushima, like the failures that preceded it, will do relatively little to undermine the credibility of nuclear risk calculations.[6] Nuclear experts and assessments have invariably found ways to 'escape' from being tarred by the evidence of technological failures in the past – ways to reasonably maintain the credibility of calculations 'proving' that future accidents will not happen, even as the consequences of past accidents loom large in the public imagination and heavy on the public purse. "Windscale was an exception," we were reassured. Three Mile Island was an exception. Chernobyl was an exception. Fukushima, too, is an exception. "Nuclear is now safe," we are told. "The calculations prove it." And the drums of 'nuclear renaissance' beat on.

Even before a year had passed, it was clear that the long-anticipated resurgence of nuclear power would survive Fukushima. Before the accident a total of 547 reactors were either proposed, planned or under construction throughout the world. By February 2012, this number had increased to 558 (Holloway 2012). That same month, Britain and France formally agreed to cooperate on nuclear power, paving the way for the construction of a new generation of power plants in the UK (Press Association 2012; BBC 2012). The same month, the US NRC approved

[4] For an overview of PRA as it is understood by the NRC, see: NRC (2007).
[5] As Sagan (2004: 944) observes: "Organizations can [marginalize] low-probability events by transforming them into assumptions of impossibility."
[6] Power (2011: 28) argues that crises damage the credibility of expertise, but if this is true, then, in the realm of technological risk assessment at least, it is rarely true for long.

licenses to build two new reactors in Georgia.[7] They were the first such approvals since the Three Mile Island accident in 1979, and were confidently expected to be followed by many others (Abernethy 2012). These decisions implied not only a continued institutional confidence in nuclear power, but also a large degree of (at least passive) consent from the public.

Through years of Charles Schulz's pensive comic strip, Peanuts, there ran a recurring scene between Charlie Brown and Lucy that offers a good metaphor for our relationship with nuclear risk assessment. In the first such strip, Charlie asks Lucy to hold a football for him to kick. Lucy obliges but then whips the ball away at the last second, causing him to fall. The scene's subsequent iterations always involve Lucy convincing Charlie that 'this time it will be different' and that he should trust her to hold the football, only for the strip to end with the same stunt. Charlie was fooled in this way for years, always giving in to Lucy's reasonable explanations and never learning the larger lesson. Western societies, we might say, have a similar relationship with nuclear expertise. We keep being asked to take a punt on calculations that then let us down, but after each failure our confidence rebounds and we bet again on 'calculative certainty' in consequential choices about our technological future.

[7] With no binding commitment to implement changes in federal requirements arising from the NRC's post-Fukushima work: A factor that led NRC Chairman, Gregory Jaczko, to cast a dissenting vote (a decision that Reuters [2011] described as "extraordinary").

Charlie Brown and Lucy from *Peanuts* by Charles Schulz
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This 'Brownian' resilience of the institutional credibility of nuclear risk calculations poses several interesting questions. Among them is what we might call the 'Lucy' question: How do accounts of Fukushima rationalize the credibility of nuclear risk assessments in the face of seemingly 'falsifying' evidence? This is the question that motivates this paper. The answer, it will suggest, lies in the fact that nuclear experts, much like Lucy, are consistently able to make compelling arguments to justify why their past failings should not count against their credibility. These arguments come in many forms and the discourse around Fukushima renders them in varying ways, but the core of this essay will illustrate, and then critique, four core rationales around which they cluster: four 'rites of nuclear redemption'. Rather than try to provide another account of the accident,[8] in other words, it will look instead at the accounts themselves: their rhetoric, their reasoning, and their relationship to wider currents in the public discourse around nuclear governance.

[8] For accounts of the accident see, eg: Osnos (2011); Strickland (2011).

PART TWO: Four Rites of Nuclear Redemption.

1. Deny the Assessments have Failed.

i. By emphasizing design basis

One way of denying that a nuclear accident constitutes a failure of its risk assessments is to simply deny there has been an 'true' accident or a 'real' risk. Sometimes such denials are straightforwardly untrue, such as when the USSR denied an accident at Chernobyl even as they evacuated the citizens of Pripyat (Perrow 2011b: 50). Such denials need not be so ostensively mendacious, however. More often, they exploit the fact that the definitions of both 'failure' and 'risk' are open to legitimate interpretation.

Take the notion of failure. It is rarely straightforward to define precisely when, or if, a complex system has definitively 'failed.' One reason for this is that all critical technologies are designed to tolerate some degree of failure. Not every blown fuse or broken valve at reactor constitutes a 'failure' of the plant or a nuclear 'accident,' for example, and risk analyses reflect this. On a deeper level, moreover, critical technologies are often designed to fail 'safely.'Reactors have containment structures designed to keep failures from becoming hazards, for instance, and risk analyses account for this as well. So it is that if an unanticipated reactor event is relatively contained, then observers can plausibly say that the plant, writ-large, has not failed, and that there was no real 'accident' that should challenge the validity of nuclear risk assessments.

The failure of Fukushima, we might think, should have been unambiguous, at least after the first few weeks, but even here there was room for interpretation. Even as the significance and extent of the disaster became apparent and undeniable, experts were still able to deny that their assessments had failed by parsing the definition of 'failure'. This was visible in the many 'beyond design basis' arguments: essentially assertions that the assessments were 'accurate' by their own definition of 'accurate'. The 'design basis' of a nuclear plant is the set of assumptions from which the engineers who design plants and the regulators who assess them work. So if the design basis states that the worst flood a nuclear plant will be subjected to is x meters, and the plant fails because it is flooded to a depth of 2x meters, then both the engineers who built the plant and the assessors who certified it can deny they have failed because the flooding was 'beyond design basis'. By this logic, the earthquake and tsunami that felled Fukushima can be cited as 'extremely improbable' events for which experts could not be expected to account: what insurance contracts refer to as an 'Act of God'. As the American Nuclear Society (2011) put it: Fukushima "...could actually be considered a 'success' given the scale of this natural disaster that had not been considered in the original design."

Take, for example, the reassurances Sir David King, the UK Governement's former cheif science adisor, that all the affected nuclear plants "acted as they were meant to, including Fukushima." And that the extremely large tsunami was "an extremely unlikely event" that overwhelmed defenses designed for much lower levels of flooding (in Harvey 2011). Or this lamentation from a consultant writing in the New American:

> "...the Fukushima "disaster" will become the rallying cry against nuclear power. Few will remember that the plant stayed generally intact despite being hit by an earthquake with more than six times the energy the plant was designed to withstand, plus a tsunami estimated at 49 feet that swept away backup generators 33 feet above sea level" (Hiserodt 2011).

The logic of these arguments is tenuous, however, especially when applied to risk assessments. The 'design basis' of a nuclear plant, almost by definition, should be an accurate representation of the conditions it will encounter in its lifetime. To say that an event was 'beyond design basis,' therefore, is essentially to say that the design basis, an integral element of the assessment, was wrong. It is difficult to see how a failure to predict a rare event does not constitute an assessment failure. (Especially considering that, as the head of Kinki University's Atomic Energy Research Institute told the Wall Street Journal: "The earthquake and tsunami […] both exceeded our engineering assumptions by a long shot" [in Shirouzu & Smith 2011]). Extreme natural hazards, after all, are precisely the kind of occurrences that engineers try to anticipate in their designs and risk assessors try to envision in their calculations.[9]

ii. By emphasizing hazard

There is another way of denying that Fukushima constitutes an assessment failure, however. One that is more compelling, if more circuitous. This is to concede the plant failed, and that assessments failed to predict that failure, but then maintain that the industry's calculations were nevertheless correct about the risk.

Assessments can be wrong about the reliability of a reactor yet correct about its overall risks because, as outlined above, risk calculations are probabilistic: a product of both the projected likelihood of a hazard and of the extent of that hazard. If the extent of the hazard is found to be lower than assessments anticipated, therefore, then the likelihood of that hazard can be higher without the overall risk increasing. If reactor accidents are more common than expected but kill

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[9] Moreover, the events in Japan, although unusual, were far from unthinkable. The 9.0 earthquake, although large, was not so unusual as to be obviously beyond consideration. The area, at the intersection of three fault lines, was long expected to be due a quake, and the quake, when it came, was only the fourth largest of the last century. Some analysts endeavored to highlight the danger (Perrow 2011b: 47).

fewer people, in other words, then it is still possible to argue that nuclear risk calculations were accurate. Although this is never made explicit, it is essentially to say that the assessments 'reached the right result for the wrong reasons.' Not the most reassuring defense, perhaps, but a defense nevertheless.

"As far as we know, not one person has died from radiation," Sir David King told a press conference in relation to Fukushima (in Harvey 2011) – a fact that has been oft-reated in editorials around the world. In the pages of The Guardian, for instance, George Monbiot repeatedly invoked this idea to defend the nuclear industry. "Atomic energy has just been subjected to one of the harshest of possible tests, and the impact on people and the planet has been small." he conludes one characteristic column (Monbiot 2011b). The Washington Post, meanwhile, reassured it readers: "History suggests that nuclear power rarely kills and causes little illness" (Brown 2011).[10]

Such claims are hotly contested, however. It is almost always possible to argue that nuclear accidents are less harmful than was predicted because assessments of their health effects are fundamentally ambiguous and contestable. These assessments depend on a series of assumptions and judgments that allow for very different – but equally 'scientific' – interpretations of the same data. (In sociological parlance, this is to say that the 'facts' of radiation hazards are 'underdetermined' by the evidence, allowing for a large degree of what Pinch [1993] calls 'interpretive flexibility.')

Because so little time has elapsed since the Fukushima disaster, the nature of this ambiguity, and the degree of flexibility it allows, are more easily illustrated by looking at Chernobyl – the human fallout of which experts have been able to study in much greater depth (with their conclusions then framing estimates of Fukushima's hazards).

To seriously enquire into the harm caused by Chernobyl is to wade boldly into a quagmire of attestation and contestation. The depth of this epistemological mire is evident in public estimates of the accident's death toll, which vary enormously even after a quarter-century of analysis. The official 1986 Soviet figure was 31 deaths, all among the reactor staff and emergency workers, but most accounts now concede a number of longer-term cancer fatalities. The current orthodoxy is probably best represented by an authoritative 2005 IAEA/WHO/UN

[10] See also eg: McCulloch (2011); Harvey (2011).

("Chernobyl Forum")[11] report, which concluded that around 4000 people have, or will, die prematurely over the longer term as a result of Chernobyl (IAEA 2005: 15).

As the report notes, however, this number is far from conclusive:

> It is impossible to assess reliably, with any precision, numbers of fatal cancers caused by radiation exposure due to the Chernobyl accident […]. Small differences in the assumptions concerning radiation risks can lead to large differences in the predicted health consequences, which are therefore highly uncertain (IAEA 2005: 7).

Perhaps unsurprisingly, therefore, the 4000 figure is widely contested. For example, two reports published the following year offer much higher figures. One estimating 30,000 to 60,000 cancer deaths (Fairlie & Sumner 2006); the other 200,000 or more (Greenpeace 2006: 10). In 2009, meanwhile, the New York Academy of Sciences controversially published a Russian report that raised the toll even further: concluding that in the years up to 2004, Chernobyl caused 985,000 premature cancer deaths worldwide (Yablokov 2009).[12] Between these two figures – 4000 and 985,000 – lie a host of other expert estimations of Chernobyl's mortality, many of them seemingly rigorous and authoritative.[13]

Such variance is possible because of the many uncertainties, interpretations and judgments involved in the production of knowledge about radiation and health, where a variety of factors make it very difficult to definitively link cause with effect, such that any conclusions are always tentative and easy to contest.

Consider, for instance, the myriad dilemmas that plague the data collection process. Laboratory studies show that the full effects of radiological damage may not be apparent for many years, or even several generations, which means there is always a dearth of tangible evidence in the wake of accidents. This long latency of radiological harm also makes data collection a complex, expensive and long-term undertaking, one that, in Chernobyl case, has been compounded by a range of factors – from poor infrastructure,[14] to active political recalcitrance.[15] Compounding

[11] The "Chernobyl Forum": constituting a group of specialists, including the representatives of the IAEA, the UN Scientific committee on the influence of atomic radiation, the WHO, other UN programs, as well as the World Bank and the staff of some of the state organizations of Belarus, Russia and Ukraine.
[12] A hailstorm of industry-led criticism later led the NYAOS to withdraw the report; many argue unjustly.
[13] The Greenpeace report (2006: 24) tabulates some of the wide array of differing estimates and correlates them to differing methodologies.
[14] The uncertainty partly stems from a lack of funds in the areas most affected and the absence, in those areas, of suitable scientific infrastructures for conducting chronic disease epidemiology. Partly it stems from an inability to track the hundreds of thousands of people who lived or worked on the site and then moved (or were moved) elsewhere in the former USSR (Barisonek 2011; Johnston 2011; Dupuy 2007: 244).

these problems further are uncertainties about what data the researchers should be collecting. Critics suggest that efforts to collect and analyze cancer data have led observers to overlook evidence of many non-cancer Chernobyl-related fatalities (eg: Johnston 2011; Greenpeace 2006; Yabolokov 2009).[16]

Even if researchers were confident they had health data that is appropriate and sufficient, however, there would remain the problem of teasing the 'signal' of the accident from the almost cacophonous noise of other trends and factors. Herein lies another round of uncertainties. At chronic levels of radiological harm it is almost impossible to pinpoint which ailments are specifically due to radiation. Cancer is cancer – it was prevalent long before Chernobyl and it presents the same way, whatever its underlying cause. It also correlates with a wide variety of factors – non-radiological pollutants; diet; lifestyle[17] – many of which are changing over time making it very difficult to definitively attribute epidemiological trends rates to a specific cause (eg: IAEA 2005: 7; Johnston 2011; Barisonek 2011). A seemingly damming rise in cancer rates, for instance, might be evidence of better reporting or changing diets rather than nuclear fallout. A motivated critic might always find grounds on which to doubt an epidemiological statistic. (The Chernobyl Forum report, for instance, notes that life expectancy "declined precipitously" in the areas most affected by Chernobyl, but attributes this drop to "reckless conduct" induced by "...exaggerated or misplaced health fears, a sense of

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[15] Many accounts attest to systematic attempts to obfuscate data. There are reports, for instance, that some former soviet officials classified relevant materials and forbid doctors to connect diseases with Chernobyl (see, eg: Greenpeace 2006: 9; Yablokov et al. 2009; Sherman & Magano 2011).

[16] Radiation has been linked to a wide range of maladies: intestinal problems, heart and circulation problems, respiratory problems, endocrine problems and impairment of the immune system, all of which can prove fatal. There may also be many iatrogenic fatalities that go unnoticed, (many of those "cured" of thyroid cancers, for instance, have their health disrupted by continuing medications and disruptions of their hormone and immune systems). Indeed, the (2006) Greenpeace report argues that cancer accounts for less than half of Chernobyl's fatalities (see, eg: IPPNW 2011; Johnston 2011). Genetic deformities among children are also widely reported, with some accounts connecting the accident to 30,000 to 207,000 deformed children worldwide, with potentially many more to come in later generations. (By some calculations, only 10% of the overall expected damage is likely to be expressed in the first generation) (IPPNW 2011: 34).

[18] Most analyses use a Linear no-threshold (LNT) model, which is endorsed by many expert bodies in the US and worldwide (eg: the US National Research Council (NRC 2006); The National Council on Radiation Protection and Measurements (NCRPM 2001); and The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000: 160).) The LNT holds that all levels of radiation pose a risk to human health to a degree that is directly proportional to dose, such that expose cumulates over a lifetime, with many small doses being equivalent to fewer larger doses (NRC 2006). Other organizations disagree with the LNT, however, preferring a "threshold model," which holds very small doses (equivalent to 'background levels') to be negligible and risk free (eg: ANM 2005). Some experts have even proposed a "radiation hormesis" model, which holds that radiation at very small doses can be beneficial because it promotes DNA repair (eg: Feinendegen 2005). These models affect definitions of 'affected areas' because the threshold model implies a 'cutoff' contamination level, beyond which there is no effect, whereas the LNT implies a much broader area – with diminishing risks but an increasing number of potential victims as the area widens.

victimization and dependency created by government social protection policies" [IAEA 2005: 37]).

The paucity and essential ambiguity of the data has meant that estimates of Chernobyl's effects depend heavily on theoretical models, but these too are contested and highly interpretive (Dupuy 2007; Johnson 2011). Most such models are founded on data from Hiroshima and Nagasaki survivors, the accuracy and relevance of which have been widely criticized (See eg: Green 2011), and all require the modeler to make a range of choices with no obviously correct answer. Modelers must select between competing theories of how radiation affects the human body,[18] for instance; between widely varying estimates of the amount of radioactive material the accident released;[19] and much more. Such choices are closely interlinked and mutually dependent. Estimates of the composition and quantities of the isotopes released in the accident, for example, will affect models of their distribution, which, in conjunction with theories of how radiation affects the human body, will affect estimates of the populations at risk, which in, in turn, will affect choices about the data that should be considered relevant. And so on, ad infinitum: a dynamic tapestry of theory and justification, where any error might reverberate throughout the system.

It is important to note, moreover, that many of the judgments embedded in hazard calculations are political by their nature, such that there can be no such thing as an entirely 'neutral'

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[19] The amount of radiation released by the accident – a factor of both the amount and the constitution of its ejecta – was itself highly contested (and still is, to some degree) (see, eg: LaForge 1997). Russian authorities originally estimated that the accident released around 50 to 80 million curies. By 1989, Time magazine had put the number at closer to a "billion or more" (Lemonick & Garelik 1989). The U.S. government's Argonne National Lab, meanwhile, were estimating a release that would put the figure at about three billion (Bukro 1986; LaForge 1997), while scientists at the U.S. Lawrence Livermore National Lab suggested four and a half billion (Norman 1986). More recently, the Scientific Director of the Ukrainian Academy of Sciences has put the number closer to seven billion (Chernousenko 1996: 127). While a senior analyst at the Union of Concerned Scientists and a former Chair of the U.S. Nuclear Regulatory Commission have each, at different times, estimated nine (LaForge 1997). Without suggesting that these numbers are equally credible, the disparity does give an impression of the ambiguity and dissent involved.

account of nuclear harm. Researchers must decide whether a 'stillbirth' counts as a 'fatality,' for instance.[20] They must decide whether an assessment should emphasize deaths exclusively, or if it should encompass all the injuries, illnesses, deformities and disabilities that have been linked to radiation.[21] They must decide whether a life 'shortened' constitutes a life 'lost'.[22] There are no correct answers to such questions. More data will not resolve them. Researchers simply have to make choices.

The net effect of all this is that the hazards of a nuclear accident can only be glimpsed obliquely through a distorted lens. All that remains are impressions, and, for the critical observer, a vertiginous sense of alarming possibility. Some claims are more compelling than others, of course, but 'truth' in this realm does not 'shine by its own lights' as we invariably suppose it ought. Quiet judgments concerning the underlying assumptions of an assessment – usually made in the very earliest stages of a study and all but invisible to most observers – have dramatic affects on its findings. With enough effort almost any assertion can be justified and almost any denied. The result being that whoever can mobilize the most cultural authority comes to define the 'facts'.[23]

In this environment it is easy to imagine how even small, almost invisible biases, might shape the findings of seemingly objective hazard calculations, and many critics argue that researchers in the past have either consciously or unconsciously exploited ambiguities to suit their institutional interests. Such claims go both ways. On one hand, it is routine for industry affiliates to maintain that environmental advocates such as Greenpeace selectively interpret evidence to exaggerate the toll of nuclear accidents.[24] On the other, a wide range of critics argue that most official accounts are authored by industry apologists who 'launder' nuclear catastrophes by dicing all evidence of their human fallout into an anodyne melee of claims and counterclaims

[20] By some estimates Chernobyl may be responsible for between 100,000 and 200,000 aborted pregnancies (IPPNW 2011: 6).

[21] As noted in Fn 16 above, many sources attribute a wide variety of illnesses to the accident, which, by some accounts, invalided hundreds of thousands of people that it didn't technically kill. For a compelling discussion of Chernobyl's wider human costs see Barisonek (2011).

[22] This is a complex problem. On one hand, it seems absurd to limit the deaths attributable to Chernobyl to those who died immediately and unambiguously from acute radiation poisoning. On the other, it is worth considering that we rarely try to hold the fossil fuel industry directly responsible for deaths attributable to global warming. (Although such a claim, of course, would be highly contentious).

[23] A potentially disturbing notion, when seen in light of Clarke and Perrow's (1996: 1052) finding that nuclear authorities try to maximize the persuasiveness of their safety assessments by making the most benign assumptions about the environment.

[24] The Greenpeace report on Chernobyl, for instance, often seems to be contested more on its sponsor's objectivity than on its evidence or argument.

(eg: Johnston 2011; Greene 2011; Fairlie & Sumner 2006; Dupuy 2007; Barisonek 2011).[25] (Although the latter position is often painted as the stuff of conspiracy theories, there can be little doubt that in the past governments have intentionally clouded the science of radiation hazards to assuage public concerns. The US Advisory Committee on Human Radiation Experiments [1995], for instance, has concluded that Cold War radiation research was heavily sanitized for political ends.)[26]

Ultimately, this issue deserves greater scrutiny than this paper can afford. So let us simply conclude that Fukushima's dangers are deeply ambiguous, and that accounts of the accident can exploit this ambiguity to duck questions about the credibility of prior risk assessments – pulling favorable numbers from the fact-figure crossfire as evidence that the wider risks of nuclear power are still within the bounds that regulators calculated.

2. Contest the Relevance of the Failure.

A second means of insulating the credibility of nuclear risk-assessment, writ-large, from the failure of one specific assessment is to establish that the failed assessment is unrepresentative of the whole. If Fukushima's (or, more widely, Japan's) risk calculations can be shown to be significantly different from other such calculations, in other words, then their failings can be theirs alone.

This reasoning, again, is most starkly visible in relation to Chernobyl. The Russian plant was a distinctive Soviet design ('RMBK') that was regulated by a state with little credibility in the West (for a range of variably rational but nevertheless evocative reasons), so it was easy for observers to survey the meltdown through gaps in the Iron Curtain and imagine that it said very little about their own practices. Hence, Chernobyl came to be understood as a 'Soviet accident, not a nuclear accident,' and it became routine for nuclear risk assessments to exclude the records of RMBK reactors from their calculations, and for nuclear experts to dismiss Chernobyl in their reasoning.[27] Shortly after Fukushima, for instance, Princeton physicist Robert Socolow

[25] When John Gofman, a former UC Berkeley professor of Medical Physics, wrote that the Department of Energy was "conducting a Josef Goebels propaganda war" by advocating a threshold model of radiation damage (Gofman 1994), for instance, his charge was unusual more for its candor than its substance.

[26] Or, as a former AEC commissioner admitted in the early 1990s: "One result of the regulators' professional identification with the owners and operators of the plants in the battles over nuclear energy was a tendency to try to control information to disadvantage the anti-nuclear side." (in Madrigal 2011: 230).

[27] As could be seen, for instance, when the Indian Nuclear Commission assured visitors to its website that: "The statistical risk from living next to an intelligently-designed (i.e., not RBMK) nuclear power plant is equivalent to driving 125 feet." [Emphasis added].(Indian Nuclear Commission online. [Accessed 2010; since removed]).

drew attention to this logic in the Bulletin of Atomic Scientists. "Chernobyl, I could pigeon-hole," he writes. "The [reactor] was a manifestation of the isolation of Russia and its obsession with self-reliance. The unwillingness of nuclear experts in the West to strong-arm the Soviets […] [A]nother disastrous outcome of the East-West divide." (Socolow 2011).

Socolow's article is notable because, having highlighted the case for Chernobyl's irrelevance, he then declines to extend the logic of exceptionalism to the crisis unfolding in Japan. "I can find no escape from Fukushima Daiichi," he concedes (Socolow 2011). This concession was unusual, however, for most accounts do find ways to paint Fukushima as an exception. They have had to be more creative – given that the plant was designed by General Electric in the United States, and was almost identical to two-dozen others that had been assessed and approved by US authorities (Marvel & May 2011: 3) – but they manage nevertheless. It is not illogical, for instance, to say that assessments that deemed a design safe for the US might have found it unsafe for Japan; and many commentators have invoked this logic to portray Fukushima as a 'Japanese' rather than a 'nuclear' accident (Gusterson 2011). Soon after the plant began to fail, for instance, the New York Times quoted Republican Senator Mitch McConnell opining that "...we ought not to make American and domestic policy based upon an event that happened in Japan" (in Broder 2011).

McConnell's claim might look stretched, given the providence of the reactor, but the 'Japanese disasters are not relevant' argument has gathered a lot of momentum. As Greene (2011) observes, coverage of Fukushima now routinely targets what happened "over there" while neglecting what goes on "over here". Some accounts justify this by highlighting differences in local geological condition: pointing, for instance, to Japan's seismic activity. Others stress distinctions between US and Japanese regulators. Many, for example, point out that the Japanese nuclear regulator (NISA) was subordinate to the Ministry of Trade and Industry, and argue that this created a conflict of interest between NISA's responsibilities for safety oversight and the Ministry's responsibilities for the promoting of nuclear power (eg: Marvel & May 2011; Adelstein & McNeill 2011; Ichida et al. 2011; Monbiot 2011).[28] The Carnegie Endowment for International Peace marked the anniversary of Fukushima by publishing a report that draws several of these tropes together to argue that many countries protected their nuclear plants much more effectively than the Japanese (Acton & Hibbs 2012: 1).

Some 'arguments from relevance' take a different tack – applying it not to Japan but to the Daiichi plant itself, despite the reactor's trans-national heritage. Accounts in this vein often

[28] NISA had recently been criticized by the IAEA for a lack of independence, in a report occasioned by earthquake damage at another plant (IAEA 2007).

highlight the plant's age and point-out that reactor designs have changed over time, presumably becoming safer. British columnist George Monibot (2011b), for instance, described Fukushima as "A crappy old plant with inadequate safety features was hit by a monster earthquake and a vast tsunami" and argued that its failure should not speak to the integrity of later designs like that of the neighboring plant, Fukushima 'Daini', which did not fail in the Tsunami. "Using a plant built 40 years ago to argue against 21st-century power stations" he writes "is like using the Hindenburg disaster to contend that modern air travel is unsafe" (Monbiot 2011). Many reports of Fukushima reiterate this basic idea. In the US, for instance, ABC News ran reports about three GE nuclear engineers who resigned because of defects in the Mark 1 (in Grossman 2011).

Although logically consistent, such arguments-from-relevance are often far from conclusive. Regarding national safety cultures, for instance, it is worth noting that Japan had a first-class reputation for managing complex engineering infrastructures. (As the title of one op-ed in the Washington Post put it: "If the competent and technologically brilliant Japanese can't build a completely safe reactor, who can?" [Applebaum 2011]). It is also worth noting that there is a tradition of accident observers pointing to national variations in safety practices only to have those claims rejected on further scrutiny (see, eg: Silbey 2009: 349; Perrow 1999: 358). Prior to Chernobyl, for instance, the Soviet nuclear industry had invoked arguments about the relevance of Western safety cultures to argue that Three Mile Island could never happen in the USSR (Schmid 2011a).

Arguments questioning the relevance of the reactor design itself, meanwhile, might offer a compelling rationale that some plants are safer than Fukushima, but they have only marginal relevance to the credibility of risk assessment as a practice. It is true that assessments have evolved with the technology – such that those that governed Daiichi's initial approval are no longer characteristic of assessment practices more generally (as a UK civil servant wrote in an internal email, later printed in The Guardian: "We need to […] show that events in Japan, whilst looking dramatic, are all part of the safety processes of this 1960's reactor.")[29] – but it is also true that successive assessment regimes had periodically reviewed and reassessed the risks old and new plants using common metrics and calculative criteria.[30] In theory, at least, claims about Fukushima's safety should have been based on the very latest assessment models.

[29] See: http://www.guardian.co.uk/environment/interactive/2011/jun/30/email-nuclear-uk-government-fukushima?intcmp=239

[30] Even the 'irrelevance' of Chernobyl's design has started to crumble under sustained scrutiny. Schmid (2011a; 2011b), for instance, argues that the Soviet nuclear complex was highly competent and is better understood as 'different' rather than 'inferior' to its Western equivalents. Ramana (2011), moreover, points out that three years

If it is difficult to find a discontinuity between a specific failed assessment and the assessment regime in general, however, then it is always possible to create such a discontinuity by changing the assessment regime itself. This leads to a third rite, more easily summarized than the others:

3. Admit a Flaw but Assert a Remedy.

"If nuclear power is to have a future in this country," declared a New York Times editorial after the accident, "Americans have to have confidence that regulators and the industry are learning the lessons of Fukushima and taking all steps necessary to ensure safety" (NYT 2011). This sentiment neatly captures a third approach to redeeming risk assessments, which is to concede that there was an error in the calculations (in their assumptions about tsunamis, for instance) and then argue that experts have identified the error, altered the assessments and remedied the problem. In this way, past assessment failures can be made irrelevant to the credibility of current risk assessments, and experts can deny that nuclear PRA is flawed in principle or unrealizable in practice.

Such arguments are almost always apparent in the commentary around Fukushima. In the immediate aftermath of the accident, for instance, various nations and institutions announced plans to review their risk assessment practices.[31] The NRC publicly conceded that its assessments "do not adequately weigh the risk of a [a threat to the emergency generators]" and began reframing them accordingly (Wald 2011). The EU, meanwhile, announced plans to reassess all its nuclear plants (Willsher 2011), while the IAEA promised to implement a worldwide review of nuclear risks. More recently, the 2012 Carnegie Endowment report – entitled "Why Fukushima Was preventable" – outlined a catalogue of assessment failings, which, it suggests, might be prevented in the future by "...periodically reevaluating plant safety in light of dynamic external threats and of evolving best practices" (Acton & Hibbs 2012: 2). "In the final analysis," the report concludes, "the Fukushima accident does not reveal a previously unknown fatal flaw associated with nuclear power" (ibid.).

before the accident, the head of the IAEA's safety division had written of the RMBK design that "...a serious loss-of-coolant accident is practically impossible."

[31] It is also common to see promises to fix flaws in plants rather than in the assessments, such as the American Nuclear Society's (2011) reassurance that: "The nuclear power industry will learn from this event, and redesign our facilities as needed to make them safer in the future." But these arguments do nothing to redeem the credibility of risk assessments.

Again, however, there are many reasons for skepticism. To prove that a specific accident is preventable is not the same as to prove that accidents, in general, are preventable. To argue from analogy: It is intuitive to imagine that any specific crime might have been avoided but we would not deduce from this that crime, the phenomenon, is eradicable. "The Japanese radiation victims and the dead plant workers will be glad to know that in their disaster lies our salvation" writes Perrow (2011a). He is being arch, of course, but he has a point. Nuclear risk assessments promised that Fukushima would not happen. From a critical perspective, arguing that we should not judge these assessments on the basis of one large meltdown might be considered analogous to arguing that we should not label someone a murderer on account of one regrettable homicide. It begs the question of when failure is truly definitive. If the Cold War had nadired in a thermonuclear exchange, as it almost did too often to contemplate (eg: Rhodes 2010), would the ensuing genocide have wholly invalidated the dogma of 'deterrence,' or merely suggested it needed refinement?

Even if we assume – over the objections of many theorists (eg: Perrow 1999; Downer 2011b) – that nuclear risk assessments can aspire to be entirely accurate, and that after the refinements prompted by Fukushima they might be perfect, how are we to know for sure? The 'we found the flaw and fixed it' argument offers no 'in principle' reason to believe that there will be no future lapses. It gives us no way of knowing how many 'lessons' the future might hold.[32] Perhaps more purely than any of the other 'rites' outlined in this paper, therefore, it appeals for us to follow Charlie Brown in subordinating our experience to hope; to disregard the history of nuclear regulation, which is one of continuous learning from accidents and near accidents (Perrow 2011b: 51-2), and to imagine that this time it will be different. As Gusterson (2011) puts it: "the lesson of Fukushima is […] that the perfectly safe reactor is always just around the corner."

4. Highlight Noncompliance.

While promising to revise their assessment practices in response to Fukushima, many authorities also promised to implement managerial reforms. The IAEA, for instance, hastily announced a 'five-point plan' to strengthen reactor oversight through measures such as expanded international peer-review (Amano 2011). In doing so, they illustrated a final route to rescuing the credibility of technology assessments from failure: which is to argue that the

[32] Especially where the service data is statistically slight, as it is in the nuclear industry (see Downer 2011b; Ramana 2011).

calculations were sound but that people (operators, regulators, etc), either by accident or on purpose, disobeyed the rules.

Malpractice is a common theme of almost all accident investigations (Silbey 2009: 344) and nuclear accidents are no exception. The Soviet establishment blamed Chernobyl on human error, and sentenced six operators, including the plant director, to long prison terms (Schmid 2011a: 20). Socolow (2011) recalls rationalizing Three Mile Island in a similar fashion: a "teething accident" resulting from "appalling deficiencies in worker training." And Fukushima has followed a similar path. Accounts of its causes almost always highlight some evidence of human error or malfeasance. There are many examples of this, but perhaps the most prominent such claim has been an assertion that TEPCO (the operator) covered-up a series of regulatory breaches over the years, including data about cracks in critical circulation pipes that could have been instrumental in the catastrophe (eg: Adelstein & McNeill 2011).

Highlighting human failure can be a way of redeeming risk assessments after accidents because all such assessments assume, within certain bounds, that the people operating systems will strictly adhere to rules (Downer 2011a: 276-7). (Or, at minimum, that people will only violate those rules in predictable and circumscribed ways).[33] The assessments embody implicit (and sometimes explicit) caveats such as: "...given proper maintenance," or "...if handled correctly" (Downer 2011a: 276). Given that we routinely accept these caveats, therefore, observers are able to highlight operator-error, noncompliance or malfeasance without undermining the assessments themselves.

All risk assessments imply models of social behavior. Imagine, if you will, that a desperate motorist opts to speed her Toyota Prius off the edge of the Grand Canyon in a terminal but carbon-conservative leap of triumphal defiance. In this hypothetical misadventure it stands to reason that the driver's death would not undermine Toyota's calculations of its car's risks. Any reasonable observer would surely agree that automobile risk assessments are justified in assuming that people will not deliberately drive their cars off the Grand Canyon. Now, by the same reasoning, we might say that the meltdown of a reactor due to gross negligence by its operator should not reflect poorly on any calculations of that plant's risks.[34] Nuclear risk assessments all assume that reactor operators will not deliberately cover-up evidence of cracks in critical piping; they make no secret of this.

[33] It is understood, for instance, that pilots get tired and sometimes respond inaccurately when under pressure, and this is why rules stipulate (and risk assessments assume) that there be two in a cockpit to share loads and check each other's work.

[34] In a sense, this argument is another special case of Rite 2 above. Evidence of error and malfeasance detracts from the idea that risk assessments have failed because it allows observers to question the relevance of a failure.

If considered more deeply, however, this logic becomes slippery. It is reasonable for Toyota to assume that nobody will be driving off the Grand Canyon because spectacular vehicular suicides are, by any standard, unrepresentative of normal driving. But what is 'normal'? All sorts of collisions are not 'supposed' to happen, but are nevertheless routine. People drive their cars into the back of other cars all the time. Such accidents involve errant behavior, certainly, but they happen often enough that we would think it unreasonable if Toyota's risk analyses failed to model them.[35] Ford was roundly chastised for ignoring the possibility that its Pintos might explode when rear-ended.[36]

Even if all risk assessments make assumptions about human performance, therefore, the legitimacy of the assumptions rests on a conception of what constitutes truly 'aberrant' behavior. With this in mind, it is important to ask whether the kinds of errant behavior that nuclear risk assessments ignore is 'Grand Canyon' malfeasance, or whether it is the 'normal' deviance of daily operation? Pointing to unreported cracks should only serve to redeem nuclear risk assessments, in other words, if we might reasonably describe failures like 'imperfect crack reporting' as exceptional – so exceptional that risk assessments could not have been expected to account for them. If such failures are a normal, endemic and unavoidable aspect of nuclear practice, on the other hand, then they are more like routine traffic accidents than they are like Grand Canyon leaps, and, thus, deserve to have been modeled.

Most accounts of Fukushima treat its apparent human failures as if they were indeed truly aberrant. For all the editorial consternation they inspire, however, the kinds of behavior they document are arguably quite unexceptional. Malpractice and error, in varying forms, are recurrent themes of accident investigations, as we saw above, and they also feature prominently in many accounts of routine technological practice. In the nuclear industry alone, there exists a long literature documenting regulatory failings (eg: Perrow 2007), and the media spotlight generated by Fukushima has predictably unearthed further evidence of malpractice in plants around the world (eg: Donn 2011).

Indeed, there is every reason to believe that all complex technological systems will be prone to a spectrum of human failings. Over the last thirty years, a large and sophisticated body of academic literature has emerged that explores how human-error, noncompliance and malfeasance relate to accidents. Vaughan (1996), for instance, speaks of the "normalization of deviance"; Rasmussen (1997) of "migration to the boundary"; and Snook (2000) of "practical

[35] And, as Wetmore (2004) highlights, the definition of "reasonableness" in technological risk analyses is itself a dynamic and negotiated construct.

[36] Toyota, (like Ford today), no doubt does model such contingencies, and has probably run commercials starring crash-test dummies.

drift." This discourse[37] sometimes conveys a diffuse impression – usually implicit and often unintentional – that human behavior is a manageable problem: "something akin to noise in the system" as Silbey (2009: 342) puts it. Yet it is a problem than has proven stubbornly resilient to sociologists' proscriptions. The 'error-free safety-culture' continues to elude systems managers. Indeed, it is difficult to imagine any institution in history in which every rule was followed all of the time. (Adherents of the Old Testament believe that the very first two humans on Earth disobeyed their only rule; commanded unto them by God Himself.)

This enduring failure to solve the 'human problem,' becomes more understandable when seen in light of close accounts of technological work, which routinely finds it to be necessarily and unavoidably 'messier' in practice than it appears on paper (eg: Perrow 1983; Perrin 2005; Langewiesche 1998; Downer 2007; Wynne 1988).[38] The idea of perfect rule compliance, these studies point out, implies that complex institutions can realistically offer unambiguous rules that proscribe actions for every contingency, whereas experience shows that even the most expansive stipulations sometimes need interpretation and cannot relieve workers of having to make some decisions in uncertain conditions (Schmid 2011a; Mackenzie 2003). "Regulations will always be imperfect," writes Perrow (2011b: 46), "they cannot cover every exigency."[39]

Setting aside the issue of 'normal' human failures, moreover, it is worth noting that even truly aberrant human failings have a complex relationship to nuclear risk. For, in this context, it is doubtful whether assessments are even justified in ignoring 'Grand Canyon' malfeasance. Cars are not expected to be safe against people who choose to destroy them, but nuclear reactors are. Given the dire consequences of a meltdown, risk assessments cannot discount the possibility that someone will do something self-destructive and genocidal. The nuclear industry recognizes this. It studies 'insider threats' and the resilience of 'containment structures' to the impact of errant airliners, even while it fails to fully incorporate them into the Probabilistic Risk Assessments on which we frame policy.

The relationship between risk assessment and human behavior should be much more contentious than it is.

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[37] Of which Silbey (2009) offers a useful overview.

[38] Thus both human error and non-compliance are ambiguous concepts. As Wynne (1988: 154) observes: "...the illegitimate extension of technological rules and practices into the unsafe or irresponsible is never clearly definable, though there is ex-post pressure to do so." The culturally satisfying nature of 'malfeasance explanations' should, by itself, be cause for circumspection.

[39] A fact that leads many scholars to attribute their pervasiveness in accident investigations as much to institutional expediency as to human deficiency. Perrow (1983; 1999 [1984]), for instance, offers compelling accounts of how institutions often try to limit their liability for accidents by leveraging inherent ambiguities in the definition of 'operator error'. As the sociologist Ulrich Beck notes when surveying the roots of technological disaster: "...human error rather than system risk can [always] be cast as villain of the piece" (1999: 151).

PART THREE: The Nettle Of Uncertainty

Noting that public faith in nuclear power seems incommensurate with the technology's checkered history, Grandazzi (2006) laments that "Facts are no better than words in changing [our understanding]." He attributes this to a form of ideological stubbornness and denial, but the truth is more subtle and insidious: it is that there are no entirely objective technological 'facts'. Even nuclear disasters must be contextualized and interpreted before they can speak meaningfully to us. Somewhere there must be an ontological 'truth' of technological risk, and scientists and engineers may be (by far) the people best able to assess it, but such truths can only be viewed through layers of interpretation, much of it contestable. As Sloterdijk (2000: 108) has suggested: "The only catastrophe that would be clear to everyone would be the catastrophe that no one survives".[40]

So it is that no failure, however spectacular, can definitively kill the credibility of nuclear risk assessment as a practice. Accounts can always shield it from potential evidence of its failures by invoking one of four rites. Specifically, claims that:

1) The assessments did not fail because the accident (or its consequences) was within the bounds they predicted.

2) Most (or 'our') assessments are meaningfully different from those that the accident showed to be erroneous – such that any failed assessments should not undermine the practice of assessment more generally.

3) Assessment practices (or logics) were indeed flawed, but the flaw has been identified and remedied, and now assessments can be trusted.

4) The assessments were accurate but people broke the rules on which they were justifiably premised, and new measures can ensure that this will not occur in the future.

These rites are deeply woven into our accident narratives, usually in overlapping ways (the real world rarely fits comfortably into conceptual taxonomies).[41] Take, for example, this sentence from the New Yorker, which implicitly couples the notion that people, not assessments, were at

[40] "La seule catastrophe qui paraît claire à tous serait la catastrophe à laquelle personne ne survit"

[41] There is a degree to which they overlap conceptually as well. From a reductionist philosophical perspective, for instance, it is arguable that rites 3 and 4 are both essentially variants of rite 2, in that all three are ultimately ways of contesting 'relevance'.

fault (Rite four), with the notion that Japanese failings might be unrepresentative of nuclear power more generally (Rite two).

> "...the Fukushima meltdowns, the world's worst nuclear accident in twenty-five years, were man-made, the consequence of failures that laid bare how far Japan's political and technological rigor have drifted from their apex" (Osnos 2011: 60).

We should note that the author of this line was probably not consciously attempting to redeem the credibility of risk assessments.[42] It is also important to recognize that the claims he makes might well be true. Indeed, there is no escaping from the fact that the four basic arguments outlined above are often logical and useful. The ambiguities of nuclear fallout mean that risks could be within the predicted limits. Assessment practices do differ in ways that limit the broader relevance of specific failures. Risk calculations undoubtedly do improve with the lessons of experience. People do undermine calculations if they break prescribed rules. All of these claims are potentially valid, even if, as we saw above, they are not always very compelling. They serve a useful function. It is vital, in the aftermath of accidents, that we highlight errors and wrongdoing; hone assessments by identifying errors; endeavor to more accurately weigh evidence of harm; and highlight ways that assessment regimes differ.

It is important to understand, however, that these arguments can all be logical in principle, and even credible in practice, but still miss a much more fundamental truth: that there are too many judgments folded into nuclear risk assessments for those assessments to be trustworthy or credible. The truth that Charlie Brown can never know for sure if Lucy will hold the football steady, no matter how convincing her assurances or how compelling her recantations.

That idea that technological 'risk' is a variable like 'mass' or 'velocity' that can be determined by formal rules and objective algorithms pervades our civic discourse. Gherardi and Nicolini (2000: 343) call it the "bureaucratic vision of safety"; Dupuy, more poetically, has referred to it as the "metaphysical pride of modern humanity" (in Grandazzi 2006). Porter (1995) and others, and call it the 'Ideal of Mechanical Objectivity'. It is most directly evident in the declarative statements of authority that often characterize semi-private expert pronouncements about technological risk, such as "The math is the math," or "It's not an opinion, it's a calculation." It is more publicly visible in authoritative proclamations that have been carefully couched in accessible analogies, such as claims that 'living next door to a nuclear plant for 50 years' is as

[42] To be sure, however, commenters do sometimes frame their accounts with the conscious goal of reassuring the public (although not necessarily with cynical motivation); as was illustrated, to some embarrassment, when The Guardian published internal emails from the UK civil service. (See: http://www.guardian.co.uk/environment/interactive/2011/jun/30/email-nuclear-uk-government-fukushima?intcmp=239).

risky as 'driving 125 feet'; 'eating a ham sandwich,' or 'living with a smoke detector' (eg: NRC 2005). More pervasively but less visibly, it is evident in what these statements imply: a routine deference to the idea that experts, in principle, can take an enormously complex system – one with sophisticated socio-organizational dimensions and a stochastic operating environment – and assess its risks to seven decimal places (the level implied by the projected accident frequencies).

As indicated above however, there are many compelling reasons to imagine that this ideal must be wrong, and that formal risk calculations have fundamental limitations. Many of these reasons are best articulated by social scientists, several of whom have long-sought to articulate why complex systems must harbor risks that escape the calculus of formal assessments. The most prominent such argument stems from Normal Accident Theory (NAT) (Perrow 1999 [1984]),[43] with its simple but profound probabilistic insight: that accidents caused by very improbable confluences of events (that no risk calculation could ever anticipate) are 'normal' in systems where there are many opportunities for them to occur. A different approach has been to point to the irreducible epistemological ambiguity of technological knowledge, and show that the significance of this ambiguity is magnified in assessments of complex, safety-critical systems due to: (a) The very high levels of certainty these assessments require;[44] and (b) The need for them to work without statistically-relevant service data (Downer 2011a).[45] Viewed from this perspective, it becomes apparent that complex systems will be prone to failures arising from erroneous beliefs that are impossible to predict in advance (what we might call 'Epistemic Accidents') (Downer 2011b).

The same conclusions are also evident in the engineering discourse, however. Technical experts in different spheres have long highlighted the limitations of PRA numbers, which are treated as heuristic fictions by most engineering organizations that work with complex systems, especially NASA.[46] Even reports sanctioned by the NRC periodically criticize the use of PRA. In 1978, for

[43] See also: Sagan (1994); Downer (2011b).
[44] Judgements become more significant in this context because they have to be absolutely correct. There is no room for error-bars in such calculations: it makes little sense to say that we are 99% certain a reactor will not explode, but only 50% sure this is correct.
[45] Judgements become more significant in this context because a lack of service data means that calculations have to be projections into the future rather than inferences from the past (Downer 2011a). (The reliability required of reactors is so high; the number of reactors in operation is so small; and the variation between designs is so extensive, that, even after half a century of operation, data about their performance is statistically inconsequential. [see, eg: Ramana 2011].) This, in turn, multiplies the number of judgments and assumptions the calculations require.
[46] In most engineering contexts, PRA is regarded as a 'decision support tool': a process that helps managers identify weaknesses in complex systems and prioritize expenditure, rather than a means of definitively establishing risk (see eg: NASA 2002: 2). In this 'decision-support' construal, PRA serves a similar function to some

instance, the agency sponsored an ad hoc 'Risk Assessment Review Group' (RARG), which announced in its report that nuclear risk assessments were failing to "sufficiently emphasize the uncertainties involved" in their findings, with the effect that PRA was being "...misused as a vehicle to judge the acceptability of reactor risks" (RARG 1978: ix-x).

If none of these arguments about the limits of our engineering certainties has had much influence on the credibility of nuclear risk assessments, then it is easy to imagine why. NAT has been enormously influential in many academic circles, as have (in a broader sense) the arguments of epistemologists about the contingencies of proof. Yet social scientists speak with limited cultural legitimacy when they speak about technical knowledge, and it is unrealistic to expect technical experts and institutions to undermine their own credibility and self-interest in a sustained way.[47] This, ultimately, is why accident accounts are significant. The disaster-punctuated history of critical technologies ought to speak for itself about the limitations of risk assessments, but our narratives emasculate that history. The rites of redemption allow accounts to rescue the credibility of risk assessment from its failings, and, in doing so, they reify the idea that accidents are aberrant and avoidable rather than endemic.

This mirage of 'perfect risk assessment' is especially consequential in respect to nuclear power. Our policymakers base enormous societal decisions on the assumption that expert calculations can objectively and precisely reveal the truth of nuclear risks. When accounts of nuclear accidents elide the limitations of risk calculations, therefore, they are not only misleading, they are damaging. They undemocratically exclude observers from participating in decisions that affect their lives, by framing debates on nuclear risks in ways that hide uncertainties from public discourse (Weingart 1991: 11; Pélopidas 2010). They also shape bureaucratic structures in ways that sometimes encourage perverse policy choices. States inevitably constrain their policy options when they formally and authoritatively 'deny' a specific hazard, because it is difficult – legally, bureaucratically and rhetorically – for policymakers to justify, or regulators to require, consideration of risks that have been officially declared to be insignificant.[48] To quote Power (2011: 29): "A society which seems to manage risk via the intensification of auditing and

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organizational tools – such as a tradition of holding regular group meetings without senior managers present. Proponents of PRA, understood this way, would never claim it offers a means of authoritatively determining the likelihood of highly consequential failures in complex systems to a level of certainty that communities can bet their lives and livelihoods on.

[47] Critical reports like the RARG's are quickly marginalized.

[48] Planning and preparing for disasters can be enormously expensive, and so there is much incentive for industry to avoid doing so, especially if their liabilities are limited. In a sense, the assessments create a "legal straitjacket" for the state, which must operate within the logic of its own pronouncements. (Or, at minimum, cannot be held accountable for not operating within that logic. Plaintiffs struggle to sue industries for being unprepared for events that have been legally dismissed.) As Power (2011: 29) argues: when states publicly vest in the idea that they can accurately audit risks, they limit their freedom to prepare for surprises.

monitoring, in fact makes itself more vulnerable by damaging the institutional conditions for encountering fundamental surprise."

The perverse structural effects of the 'perfect risk assessment' myth are perhaps most visible in relation to disaster preparedness. If Fukushima illustrates anything, it is that states are poor at planning for nuclear accidents. At the plant itself, for instance, infrastructures, procedures and guidelines were woefully insufficient for a meltdown, forcing operators to respond on an almost entirely improvisational basis.[49] Japanese policymakers were similarly unready, as was evident in ill-considered announcements that were often characterized by denial, secrecy, and refusal to accept outside help (Perrow 2011b: 50). The state, more widely, was similarly underprepared, with important medications being scarce and difficult to distribute (Kubiak 2011)[50] and evacuations poorly managed (Onishi & Fackler 2011).[51]

We should be wary of seeing such failures as a specifically Japanese problem. Indeed, observers of the nuclear industry have long argued that all states routinely make choices that seem illogical if considered in relation to a potential disaster (eg: Clarke 2005; Perrow 2007). A conspicuous example would be the routine 'clustering' of several nuclear reactors into a single facility, which saves money but creates conditions where failures can propagate (Perrow 2007: 136). Fukushima demonstrated the perils of this,[52] but few observers suggest that the US was substantially better prepared for such a disaster (see, eg: Perrow 2011b: 46-7; Kahn 2011).

Such planning is never entirely absent, but it is invariably insincere and insufficient. Clarke and Perrow (1996), for instance, describe some of the evacuation planning undertaken for Shoreham Nuclear Power Station on Long Island, but argue that these plans were so unrealistic

[49] When the lights went out, for example, workers had to borrow flashlights from nearby homes to study the plant's gauges (Osnos 2011: 50). On-site dosimeters maxed-out at levels that were far below those that could be expected from a catastrophe – unable to display readings any higher. And, as the plant's former safety manager would later testify, emergency plans "...had no mention of using sea-water to cool the core" (quoted in Adelstein & McNeill 2011): an oversight that caused unnecessary, and perhaps critical, delays.

[50] Iodine tablets were widely available, but substantial hurdles restricted the use of a common purge for Cesium 137 – which experts knew from Chernobyl could pose a larger hazard than iodine (Caldicott 1994; Wagner 2011; Kubiak 2011). Doctors are counseled to use the drug – called Prussian Blue – quickly if they know or even suspect any radiocesium contamination (for which there is a simple test), but it was in chronically short supply and doctors were legally forbidden to prescribe it without a full body scan, of which they were only equipped to perform a handful (ten, by some reports) in a given day (Kubiak 2011).

[51] A failure to utilize and distribute forecasts from a computer system known as the 'System for Prediction of Environmental Emergency Dose Information', led many people unwittingly evacuated with their children to areas that were downwind of the hydrogen explosions and spent several days in areas that have been known to be dangerously contaminated (Onishi & Fackler 2011).

[52] Fukushima itself was a cluster of six reactors; a design choice that workers must have rued as failures in different reactors greatly exacerbated each other – the fallout from the first explosion creating a deadly radioactive hotzone around the ailing reactors nearby (Osnos 2011: 50; Strickland 2011).

that they are better understood not as earnest contingency preparation but as elaborate public performances: bureaucratic Kabuki.[53] And when organizations do attempt to think more earnestly about nuclear disaster – "possibilistically" as Clarke (2005) puts it – then the plans they produce invariably lack institutional authority. The NRC, for instance, has developed "Severe Accident Management Guidelines" (SAMGs) for directing reactor operations in the event of "unanticipated accident sequences" (ie: events like Fukushima), yet training in these guidelines is voluntary. At least at the time of Fukushima, the NRC did not require that operators demonstrate any knowledge of the SAMGs or their application (Lochbaum 2011), and a recent audit of US plants found them to have been largely neglected (NRC 2011).

The indifference that characterizes national planning for nuclear meltdowns is surprising, given that Western states have embraced disaster planning more fully in many other spheres, such as flooding and terrorism (eg: Walker & Cooper 2011; Collier 2008; Duffield 2011).[54] As indicated above, however, much of the explanation for it lies in an institutionally deep-rooted confidence – born of risk assessments – that contingency planning is unnecessary in the nuclear sphere. The risks of nuclear plants are supposed to be calculable in way that the risks of terrorism are not, and the calculations show that nuclear accidents, unlike floods, will not happen. Thus, they lead institutions to 'do too little' by encouraging them to 'expect too much'.[55] As Beck (1999: 150) puts it: "our risk assessment bureaucracies have found ways to deny systemic hazards".

The idea that states might be excessively deferential to technocratic-technological expertise is hardly a new fear. Noting how risk-assessors use esoteric rites and cryptic documents to interpret opaque truths about technologies to a receptive public, for instance, Perrow describes them as "a new breed of shamans" (1999: 12). His point is not to deny their expertise but, rather, to suggest that they speak with more authority than they merit, and that this can be harmful (See also: Ramana 2011; Downer 2011a). Even Eisenhower, at the eve of his

[53] In these ways, we might say that the plans for nuclear disaster mirror those for nuclear wars (eg: Eden 2004; Clarke 1999)

[54] Over the last two decades, for instance, national governments have enthusiastically sought to enhance their preparedness for a wide range of contingencies – from transnational terrorism (Bougen 2003; O'Mally 2003) and environmental degradation (Duffield 2011), to market volatility (Beck 1992). As a result, 'resilience' has entrenched itself in the lexicon of modern governance, and become a core principle of 'good policymaking' (Walker & Cooper 2011; Collier 2008). The pursuit of resilience ends where nuclear engineering meets public policy, however. It is a common trope within nuclear engineering, where it is frequently invoked as a design principle, especially in regard to systems-level safety features (such as the hardened containment structures that enclose most nuclear reactors), but as a stratagem of nuclear governance and trope of nuclear planning it is only marginal, as Fukushima underlined. (Indeed, this can be said in regard to safety critical systems more broadly, with several spheres demonstrating a lack of accident consciousness (see, eg: Downer 2011a). In aviation, for instance, regulators allow civil aircraft to have forward-facing passenger seats despite evidence that reversing them might have saved many lives over the last fifty years [Nader, & Smith 1994: 78; Weir 2000]).

[55] Beck (1999: 141) calls this the 'risk trap'.

presidency, warned of a world in thrall to technical expertise. "In holding scientific research and discovery in respect," he admonished in his prophetic (1961) 'military-industrial complex' speech, "[…] we must also be alert to the equal and opposite danger that public policy could itself become the captive of a scientific-technological elite."

"It is the task of statesmanship," Eisenhower concluded, "to mold, to balance, and to integrate these [forces] within the principles of our democratic system – ever aiming toward the supreme goals of our free society." Robert Socolow (who declined to 'escape' from Fukushima, above) concluded his brief comments in the Bulletin of Atomic Scientists with a broadly analogous call: "[…] We scientists have only one job right now," he writes, "to help governments, journalists, students, and the man and woman on the street understand in what strange ways we have changed their world" (Socolow 2011).

These are worthwhile sentiments. The health of any democratic regime depends on the critical skills of its citizens and their representatives, and it behooves experts of all kinds to hone those skills to fit a world being transformed by technology. To be truly enlightening about events like Fukushima, however, expert accounts must reach beyond the minutiae of accidents and speak to the beliefs that surround them. Socolow suggests that Fukushima's most important lesson might be the need to "revisit the resilience of back-up systems," but this is weak. A much more fundamental lesson would speak to the role of nuclear risk assessment and the relationship between risk experts and policymakers. For if it were possible to institutionalize the idea that nuclear risk assessments are contestable judgments more than they are objective calculations, then we would be better positioned to govern the atomic age.

To learn this lesson would not require us to displace our current risk experts, but simply to alter our perception of their role, and our expectations about their abilities. There is a meaningful difference between a society that believes experts are the best voices to trust on matters of technological risk, and a society that believes that experts can offer definitive answers to inherently ambiguous questions. Most democratic decisions about complex technological systems can be made on 'the best expert opinion,' simply because we are willing to tolerate occasional failures in most systems.[56] Nuclear accidents are intolerable however, or they should be intolerable, given the highly uncertain and potentially vast extent of their hazards. Thus these technologies, in particular, call for technocratic humility. The most pertinent question with nuclear risk is not what is true, or what is probably true, but what could be true. Academic or policy debates that treat nuclear risk assessments as 'established facts' are likely to make

[56] The fundamental questions raised by an airplane crash, for instance, do not revolve around whether aviation, writ-large, is a justifiable societal risk.

very different policy recommendations than those that are willing to grasp the nettle of uncertainty.

Uncertainty demands 'possibilist' thinking (Clarke 2005). It favors the 'precautionary principle' Collingridge & Reeve 1986); and reminds us that: "as with the shamans and the physicians of old, it might be more dangerous to go to [risk assessors] for advice than to suffer unattended" (Perrow 1999: 12). We must learn to fear uncertainty, because when fear is appropriate it can be a sound adviser. It might not aid us in making nuclear power safer, but it would more adequately frame questions about whether the costs of trying are too high to bear. We might not build reactors if we were aware of their uncertainties.[57]

Rather than learn this lesson, however, we consistently evade it. Mainstream discourse around Fukushima is framed by a defensive posture. A posture that is deeply committed to the ex-cathedra status of risk assessment and technical expertise. A posture that paternalistically worries more about 'alarming' the public than about 'informing' them. A posture that too often construes 'educating the public about nuclear risk' to be synonymous with 'convincing the public that nuclear is safe' (An attitude that is exemplified by the NRC's (2004) "Guidelines For Risk Communication").[58] A posture that invokes the 'rites of redemption' to channel public discourse into narratives that allow accidents to receive extensive criticism while shielding our foundational understandings from sustained critique. These narratives are endorsed by powerful and credible voices,[59] but we should not conclude from this that there is no alternative. Witness, for instance, German debates, which have largely eschewed them (Greene 2011).

We should avoid such narratives by stepping back from the rites of redemption that shield the credibility of risk assessments from our discussions of nuclear disaster. The idea of perfect risk assessment – deeply woven into our institutions and discourse – fosters dangerous currents in the governance of nuclear power. It denies the fact that, as Perrow (2011b: 52) puts it: "Some complex systems with catastrophic potential are just too dangerous to exist, not because we do not want to make them safe, but because, as so much experience has shown, we simply cannot." For experience can only 'show' if we are willing to 'see', and the lessons of Fukushima, like those of the accidents that preceded it, will always be opaque to us if our narratives consistently interpret it as exceptional.

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[57] Undoubtedly, Japan's prime minister – harboring, he would later confess, 'apocalyptic visions of a deserted Tokyo' (Osnos 2011: 50) – must have questioned Japan's decision to invest in nuclear as he weighed the grim calculus of catastrophe and ordered the formation of 'suicide squads' to forestall a meltdown.

[58] A remarkable document that surely will one day stand alongside yellowing 'duck and cover' pamphlets in kitschy displays of the sinisterly cheerful literature of institutional denial in the atomic age.

[59] Many of whom have strong vested interests in promulgating those narratives.

There is something endearingly quixotic about Charlie Brown's enduring willingness to trust in Lucy, but where Charlie risks little except his pride when he takes a punt, some footballs we simply have to kick.

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