Towards the Pedagogy of Risk: Teaching and Learning Risk in the Context of Secondary Mathematics

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Abstract

A qualitative case study was presented in order to explore an inquiry-based learning approach to teaching risk in two different grade 11 mathematics classes in an urban centre in Canada. The first class was in an all-boys independent school (23 boys) and the second class was in a publicly funded religious school (19 girls and 4 boys). The students were given an initial assessment in which they were asked about the safety of nuclear power plants and their knowledge of the Fukushima nuclear power plant accident. Following the initial assessment, the students participated in an activity with the purpose of determining the empirical probability of a nuclear power plant accident based on the authentic data found online. The second activity was then presented in order to determine the impact of a nuclear power plant accident and compare it to a coal power plant accident.

The findings provide evidence that the students possess intuitive knowledge that risk of an event should be assessed by both its likelihood and its impact. The study confirms the Levinson et al. (2012) pedagogic model of risk in which individuals’ values and prior experiences together with representations and judgments of probability play a role in the estimation of risk. The study also expands on this model by suggesting that pedagogy of risk should include five components, namely: 1) knowledge, beliefs, and values, 2) judgment of impact, 3) judgment of probability, 4) representations, and 5) estimation of risk. These
components do not necessarily appear in the instruction or students’ decision making in a chronological order; furthermore, they influence each other. For example, judgments about impact (deciding not to consider accidents with low impact into calculations) may influence the judgments about probability.

The implication for mathematics education is that a meaningful instruction about risk should go beyond mathematical representations and reasoning and include other components of the pedagogy of risk. The study also illustrates the importance of reasoning about rational numbers (rates, ratios, and fractions) and their critical interpretation in the pedagogy of risk. Finally, the curricular expectations relevant to the pedagogy of risk from the Ontario secondary curriculum are identified.
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Chapter One: Introduction

The thesis explores ways in which mathematics educators can foster secondary school students’ understanding of risk. Specifically, I investigate students’ interpretation, communication, and decision making based on data involving risk in the classroom setting. Informed by the investigation, I consider ways in which curriculum and pedagogy can assist in the development of the teaching and learning of risk. For the purpose of exploring risk in the classroom, I draw from definitions of risk from various disciplines as well as the frameworks of statistical and probability literacy, particularly those of Gal (2004, 2005). Further, students’ learning is studied within the pedagogic model of risk (Levinson et al., 2012; Pratt et al., 2011). The thesis is framed as a qualitative case study of teaching risk in two grade 11 classrooms using an inquiry-based learning approach to pedagogy (Bybee et al., 2006; Hmelo-Silver, Duncan, & Chinn, 2007).

Research Context

Decisions based on understanding of risk are made in all aspects of life, including health (e.g., whether to continue with the course of medication), finances (e.g., paying for extra insurance), and politics (choosing between pre-emptive strikes and political dialogue). These decisions are not only common but are also critical for individual and societal health and well-being. Some studies have shown, for example, that people are routinely exposed to medical risk information (e.g., prevalence rates of diseases) and that their understanding of this information can have serious implications for their health (Rothman et al., 2008). Decision making in modern society is centred on the assessment and management of risk. Many issues, from the security of global financial markets to climate change, involve sophisticated arguments related to risk.
Despite its importance, there is a consensus amongst experts that most people are unable to adequately interpret and communicate risk (Reyna et al., 2009). The problem of improving understanding of risk has been addressed in the specific context of public health and financial counselling, yet it has only begun to be explored within educational research (Pratt et al., 2011).

Despite a recognized and urgent need for risk education, there is a lack of agreement on its definition. The concept of risk exists at the intersection of many related fields—mathematical, health, statistical, probability, scientific, and financial, among others. In this study, in terms of the pedagogy of risk, I will situate risk within the fields of statistical and probability literacy as these fields focus on uncertainty and chance, both important elements of risk-based reasoning. Most current approaches to literacy recognize it as more than a minimal subset of content knowledge in a particular field (see, for example, Gal, 2004a). Further, the definition of literacy has been expanded to include “desired beliefs, habits of mind, or attitudes, as well as a general awareness and a critical perspective” (Gal, 2004a, p. 48). Consistent with Gal’s (2004a, 2004b, 2005) research on statistical and probability literacy, I define pedagogy of risk to include knowledge (e.g., probability content knowledge) and dispositional elements (e.g., beliefs and attitudes about risk) as I examine its place within the secondary mathematics curriculum.

Researchers and policy makers have recognized the need for education about risk (Gigerenzer, 2002; Kolsto, 2001; Levinson et al., 2012; Pratt et al., 2011). Pratt et al. (2011) provide examples from the UK curricular documents which call for teachers to teach probability through situations involving risk. In the context of the Ontario secondary school curriculum, the concept of risk can be found in multiple subject areas, including science (e.g.,
students are expected to learn to analyze risk of introducing particular technology to ecosystems), physical and health education (e.g., risk involved in participation in a physical activity), and family studies (e.g., risk of contamination in food) (Ontario Ministry of Education, 2011). Given that understanding of risk includes a strong quantitative component, the mathematics classroom is an appropriate setting for the exploration of its pedagogy. However, in Ontario, mathematics curriculum documents do not focus on risk. Moreover, throughout the secondary mathematics curriculum, there are limited mentions of risk; these fall within the context of financial mathematics as well as the promotion of students’ risk taking which is considered “necessary to become successful problem solvers” (Ontario Ministry of Education, 2005, p. 24). The exploration of the pedagogy of risk has begun only recently. The most comprehensive research in pedagogy of risk was done by the researcher involved in the Institute of Education’s TURS Project (Promoting Teachers’ Understanding of Risk in Socio-scientific Issues). The research, which involved in-service teachers, problematized risk education as the interplay of mathematical knowledge, beliefs, context, and content knowledge.

**Purpose of the Study**

Despite calls for teaching risk in the classroom, and despite the explorations by the TURS research group, there remains a lack of research in the mathematics classroom setting and involving students. The purpose of this study is to address the lack of research by exploring the ways in which risk could be taught within the mathematics classroom. Specifically, this study explores the ways that secondary school mathematics instruction can support students’ developing understanding of risk, and I focus on the following guiding question:
How do secondary school students reason and make decisions about risk?

**Significance of the Research**

Research on risk within mathematics education has been focused on probability and has ignored other aspects of risk, including the importance of impact, beliefs, critical elements, and content knowledge. Moreover, the research on probability is almost exclusively conducted through the lens of deficit theory (Falk, 1989; Gigerenzer, 2002). Only recently, the TURS research program being an exemplar, has there been increased interest in the pedagogy of risk within the context of both mathematics and science education that not only acknowledges the shortcomings of deficit theory but also makes the cultural aspect of risk pivotal.

The work published by Pratt et al. (2011) and Levinson et al. (2012) has mostly focused on in-service mathematics and science teachers; this study offers an in-depth exploration of teaching risk specifically to secondary school students. It also places teaching risk in the context of the current curricula while showing how the teaching is related to the specific curriculum expectations. Consistent with the relevant pedagogic practices, the teaching is done using an inquiry-based learning (IL) approach.

The research provides insight on students’ thinking and reasoning about risk, chance, and uncertainty. I examine the pedagogic model of risk proposed by Levinson et al. (2012), explore its compatibility with the findings from this study, and suggest ways in which the model can be augmented and expanded. The revised pedagogic model of risk is also a unique contribution of the study.
Background of the Researcher

In this section, I will explain my professional and personal journey that led me to the concept and pedagogy of risk. I grew up in the former Yugoslavia. When I was eighteen, I moved to Olympia, Washington, to attend my final year of high school. After that, I moved to Seattle and attended the University of Washington and obtained a Bachelor of Science degree in mathematics. Following graduation, I spent a year working at Amazon.com and then moved to Croatia and worked for two years as a high school mathematics teacher. In 2002, I immigrated to Canada, where I worked as an elementary and high school teacher before starting graduate studies in education in 2006.

I encountered the challenge of understanding uncertainty as a learner and an educator. Despite having been considered a good mathematics student in both high school and university, I struggled with probability concepts. I attribute this to the fact that I was introduced to probability concepts fairly late in my senior year of high school. My own experience with probability prompted me to think about whether it would be more useful to introduce probability concepts at an earlier age in order to prepare students for more rigorous study of probability as well as the real-life application of probabilistic thinking.

My interest in probability continued during my master’s studies at the Ontario Institute for Studies in Education (OISE) and resulted in the master’s thesis titled “Elementary Students’ Understanding of Randomness” in which I presented a case study of grade 4, 5, and 6 students’ understanding of randomness. I interviewed fifteen students from an independent school in Ontario while they were solving multiple choice probability questions from a standardized test. My findings suggested that the students’ intuitions about randomness were highly connected to the context of each question and that the students used
the context to make sense of the uncertainty. For example, the students were given a scenario in which 8 white shirts and 2 blue shirts were placed in a bag. The students were then asked to classify the probability of taking a blue shirt “without looking” on a qualitative scale from impossible to certain. A student responded that the probability depended on how the shirts were placed in the bag, assuming that the shirts would be stacked on the top of each other rather than scattered in the bag. The student’s answer was supposed to be deemed incorrect because the implicit assumption of the question is that the shirts are placed at random.

After the experience of interviewing students, I was convinced that we should create more authentic contexts—and that the students should explore scenarios closer to their own experience. With respect to the example discussed above, we can explore a more authentic scenario in which the shirts are stacked on top of each other and then try to find the probability of the first shirt being blue. After that, we can try to determine the probability of the second shirt being blue given that the first one was blue.

After obtaining my master’s degree, I continued my doctoral studies at OISE, knowing that I was going to study students’ understanding of probability. Since I worked as a mathematics tutor at the secondary level and had insight into secondary school students’ understanding of probability, I decided to shift my focus to the high school level. Applying the lessons learned from my master’s research, I wanted to study secondary students’ understanding of probability in a real-life, authentic context.

While I was developing scenarios for more authentic tasks, I was confronted with a personal tragedy that influenced my own thinking about uncertainty. In September of 2009, Nikola, my father, died of a heart attack at the age of 59. I was present when he died—trying to revive him and calling emergency. After his death, I started thinking about what I could
have done to prevent it. I also started to think about my own personal choices—diet, alcohol, and caffeine intake and exercise—that could prevent me from living a long and healthy life.

I also did a sobering exercise of counting all of the members of my family who had suffered a heart attack, including my mother, my grandfather, and three of his brothers. Before this experience, I was quite agnostic about causation and the ability of individuals to reduce the chances of something bad happening. After the tragedy, I became resolute in my will to change my habits and “improve my odds” of a healthy life. I went to a cardiologist who suggested I was at risk of developing a cardiovascular condition. He also noted my high cholesterol and blood pressure. After that, I decided to completely stop consuming alcohol and gradually move towards a completely vegan diet.

I also started reflecting on my lifestyle in my twenties and how nonchalant I was about making some decisions (e.g., consuming a substantial amount of junk food) without thinking of the consequences. I also understood that I had been aware of probabilities and statistics, but they just did not resonate with me. I wanted to know how I could connect these experiences to my PhD research, but thinking simply about probability did not seem to be adequate. I then started to think about risk rather than probability and tried to understand the relationship between the two concepts. I read Gerd Gigerenzer’s book *Calculated Risks*, in which he concentrates on people’s misconceptions of probability and the calculations necessary to make educated interpretations of medical results, including the importance of false positives. I understood the logic and calculations, but it left me unsatisfied because, again, risk was more than the calculation of probabilities. I searched the other literature on risk in math education, but there seemed to be a total lack of relevant research.
In 2010, while I was trying to conceptualize risk, I attended my first Psychology of Mathematics, North American Chapter (PME-NA) meeting in Columbus, Ohio. Together with my colleagues from OISE, I organized a working group on probability and technology. At the working group, Cynthia Langrall, an influential researcher in the field of probability education, told me about Dave Pratt’s paper on risk that was about to be published in an influential journal. I visited Pratt’s website and learned about a research group (TURS) at the Institute of Education dedicated to the pedagogy of risk.

After reading the paper, I felt that I had finally found a suitable definition of risk and risk education, since the authors problematized risk as coordination of probability and impact moderated by personal beliefs and context. After that, I knew that I was going to investigate how these different aspects of risk play out in the mathematics classroom. This PhD thesis is the result of that investigation.

Structure of the Thesis

A review of related literature is given in the second chapter. This includes a definition of risk and a description of the utility theory and cultural theory of risk, followed by an elucidation of the pedagogy of risk from the perspective of deficit theory (Kahneman, Slovic, & Tversky, 1982) and the pedagogic model of risk (Levinson et al., 2012).

The third chapter presents a rationale for using case study methodology. This is followed by a description of the inquiry-based learning approach and its appropriateness for this study. The chapter also outlines data collection, data analysis, and ethical considerations.

The fourth chapter describes the findings and the case studies of teaching risk literacy in two different settings. In each school, Dale Academy and St. Hubertus Secondary, there were two main topics explored. The first topic was concerned with the assessment of
probability. The second topic was centred on the assessment of impact and the coordination between likelihood and impact.

The fifth chapter provides answers to the two research questions and suggests further research based on the findings.
Chapter Two: Review of Literature

In this chapter, I present a review of literature on risk and understanding of risk. The chapter begins with a definition of risk, after which I describe the utility theory (realist) approach to risk, followed by a critique of the utility theory that informs cultural theories of risk. Next, I explore perspectives on teaching risk: deficit theory and a pedagogic model of risk. I illustrate the deficit theory by describing the Bayesian reasoning and successes of deficit theories in solving simple Bayesian tasks.

After explaining the shortcomings of the deficit model, I describe the pedagogic model proposed by Levinson et al. (2012) and supported by literature on the teaching and learning of probability as well as statistical and probability literacy frameworks. I then outline the elements of the model as the theoretical and empirical supports for the model. After outlining the pedagogy of risk, I present the relevant literature on the role of context and content knowledge.

The Concept of Risk

Risk is a concept that is prevalent in many disciplines and the term ‘risk’ has been used in many distinct yet connected ways. Hansson (2009) distinguishes between five different definitions of risk: 1) risk as an unwanted event which may or may not occur; 2) the cause of an unwanted event which may or may not occur; 3) the probability of an unwanted event which may or may not occur; 4) the fact that a decision is made under conditions of known probabilities; and 5) the statistical expectation value of unwanted events which may or may not occur.

The third, fourth, and fifth definitions are the most common in mathematics. The third definition aligns with the view that a risk associated with an event is a quantifiable
uncertainty (Gigerenzer, 2002), which is equivalent to the likelihood or probability of the event. This definition of risk is suitable when the events have similar consequences, but it becomes problematic if the impact of each event is different. For example, the likelihood of a person catching a cold is relatively large but its impact on the person’s life is most likely to be minimal, whereas the likelihood of getting killed in a terrorist attack is relatively small but the impact is immense. In order to account for both likelihood and impact, proper understanding of risk requires the coordination between judgments of probability and impact (Pratt et al., 2011), which corresponds to the fifth definition, the statistical expectation. This coordination can be done informally, but also formally using mathematical representations. Symbolically, the fifth definition of risk can be written as

$$R = \sum_{i=1}^{n} p_i d_i$$

where the overall risk, $R$, of a hazard, is the sum of the products of the probability ($p$) and disutility or impact ($d$) of each event associated with the hazard (Pratt et al., 2011). For example, to assess the overall financial risk of owning a car, one would find the probability of each outcome (e.g., flat tire), multiply those by the financial impact, and then obtain the total sum of all the products. The approach based on the above formula is known as the utility theory of risk (Levinson et al., 2012) and is the standard approach in technical risk analysis (Moller, 2013).

**Cultural Perspectives**

Utility theory and technical risk analysis are not the only approaches to risk. Technical risk analysis, which is a domain of philosophy, statistics, and economics, has been extended to risk governance which involves actors’ understanding and handling of risk (Lidskog & Sundqvist, 2013). However, risk governance is a complex task, particularly in
the case of global risks such as terrorism, catastrophic weather due to climate change, financial meltdown, and nuclear accidents such as the radiation leakage due to the Fukushima nuclear disaster. The anticipation of global risks can seldom be determined using methods of science. The less we are able to calculate risk, the more the balance shifts toward the cultural perspectives on risk (Beck, 2009). It follows that assessing risk goes beyond the utility theory. Assessing risk in the vast majority of social situations involves more than individual considerations of maximizing utility; rather, it is a dynamic consensus-making political process involving diverse actors and contexts (Douglas, 1992). Consistent with the cultural perspective on risk, “sociology opposes any kind of reification of risks, in which risks are lifted out of their social context and dealt with as something uninfluenced by the activities, technologies, and instruments that serve to map them” (Lidskog & Sundqvist, 2013, p. 77).

**Beyond Utility Theory and Cultural Theories**

Reality is “neither reducible to something out there, beyond human action, nor reducible to something in there, to human thoughts and actions” (Lidskog & Sandqkvist, 2013, p. 98). Reification of risk—the belief that risk is void of social context—is problematic. However, the social purification of risk the notion that risk is just the product of social factors (Lidskog & Sundqvist, 2013)—is also problematic. The question, then, is how to reconcile naïve realism and idealism. The third way should not be obtained by the combination of constructivism and realism. Instead, the focus should be on “the dynamic interplay between different factors that make up reality” (Irwin & Michael, 2003; Latour, 1993, 2004, 2005). Latour suggests that one can transcend the perceived dichotomy between utility and cultural theories by focusing on the production of risk:

Risks are produced by practices, by actors using instruments and technologies. It is therefore misleading as a sociologist to focus on perceptions, opinions and
experience. Instead, the focal point for sociology should be to explore how risks are produced, by what means and with what effects. (Lidskog & Sundqvist, 2013, p. 99)

Recently, technical risk analysis has recognized the importance of cultural theory and has treated values (individual or collective) on par with empirical data. For example, the structured decision-making approach (Gregory et al., 2012) takes into account the complexity of environmental decision making by considering uncertain science and multiple stakeholders’ values and priorities.

In addition, the precautionary principle (Wiener, 2002) can serve as a mechanism to support decision making when there is a lack of scientific evidence. The precautionary principle states that "when an activity raises threats of harm to the environment or human health, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically" (Science and Environmental Health Network, 1998).

**Teaching and Learning of Risk**

The tension between the utility and cultural theories is reproduced in the teaching and learning of risk. In the following section, I discuss the two predominant approaches to the teaching and learning of risk: deficit theory of risk (utility approach) and pedagogical approach (Levinson et al., 2012).

**Deficit Theory of Risk**

If we accept the assumption of utility theory that there is such thing as objective or actual risk, then the goal of risk education is to evaluate the learner’s perceived risk and, through cognitive adjustment, to align it with actual risk (Levinson et al., 2012; Lidskog & Sundqvist, 2013). The deficit theory has been successful in solving problems that are well defined—in other words, the problems for which there is a unique solution, such as a subset
of problems involving Bayesian inference (Gigerenzer, 2002; Kahneman, Slovic, & Tversky, 1982).

Bayesian inference is closely tied to the concept of conditional probability, a mathematical concept describing the probability of an event given that another event has occurred. Conditional probability plays an important role in understanding risk because in everyday situations the probability of one event is often contingent on the probability of another. For example, the probability of contracting the flu virus is contingent on many factors (e.g., the strength of one’s immune system, whether or not a person has received a vaccine, etc.). The conditional probability of Event A given Event B is defined using the formula:

\[ P(A | B) = \frac{P(A \land B)}{P(B)} \]

Within the context of my research, similar to Zhu and Gigerenzer (2006), I am concerned with an elementary form of Bayesian inference involving a binary hypothesis (e.g., disease or no disease) and binary data (e.g., testing positive or negative). In this case, Bayes’ theorem connects the conditional probability of B given A (posterior probability) with the prior data, including its inverse, the conditional probability of A given B:

\[ P(B | A) = \frac{P(A | B)P(B)}{P(B)P(A | B) + P(B')P(A | B')} \]

In this thesis, this elementary form of Bayesian reasoning will be referred to as a simple Bayesian task.

There are several exemplars of the simple Bayesian task that have been explored at length. The first one is Eddy’s (1982) breast cancer problem. It consists of the binary
hypotheses (cancer or no cancer) together with the binary data (positive or negative). The problem is often stated as follows:

1% of women at age forty who participate in routine screening have breast cancer. 80% of women with breast cancer will get positive mammograms. 9.6% of women without breast cancer will also get positive mammograms. A woman in this age group had a positive mammogram in a routine screening. What is the probability that she actually has breast cancer?\textsuperscript{1} (Yudkowsky, 2003)

Another exemplar often used in the literature involves drawing objects (e.g., balls) with and without replacement problems (Fischbein & Gazit, 1984). For example, the following item is designed for the purpose of investigating students’ understanding of conditional probability:

Two black marbles and two white marbles are put in an urn. We pick a marble at random from the urn. Then, without putting the marble in the urn again, we pick a second marble at random from the urn. The participants are then asked two questions: 1) If the first marble is white, what is the probability that this second marble is white? 2) If the second marble is white, what is the probability that the first marble is white?\textsuperscript{2} (Falk, 1989)

Research has repeatedly documented that a large percentage of individuals are unable to obtain correct results to these types of problems. For example, Eddy (1982) reported that 95% of medical doctors in an informal sample estimated that the answer to the breast cancer problem is around 75% where, in reality, it is around 8%. Kahneman, Slovic, and Tversky provided evidence that intuitive errors proceed from applying certain heuristic principles that often lead to erroneous probability judgments (see, for example, Kahneman, Slovic, & Tversky, 1982). For instance, according to the representativeness heuristic, people assess the probability of an event according to the extent to which this event’s description reflects the

\textsuperscript{1} The detailed solution is given in Appendix A.

\textsuperscript{2} The detailed solution is given in the Appendix B
way they perceive the set of its most likely consequences, or alternatively, the process that produces the event (Kahneman, Slovic, & Tversky, 1982). As a consequence of the representativeness heuristic, people tend to neglect the base rates which are, according to Bayes’ theorem, relevant to the calculation of probabilities.

Following ’s research, other researchers have documented various misconceptions students are likely to commit when doing conditional probability tasks. Besides the base rate fallacy discussed above, the misconceptions are inverse fallacy, fallacy of the time axis, causal conception, confusion of independence and mutual exclusiveness, and confusion of conditional probability and joint probability. According to the inverse fallacy (Koehler, 1996), also known as the fallacy of the transposed conditional (Falk, 1989), the conditional probability of Event A given Event B is taken to be equivalent to the conditional probability of Event B given Event A. The fallacy of the time axis (Falk, 1989), or the chronological conception (Gras & Totohasina, 1995), is the belief that an event cannot influence an event that occurred before it. The causal conception (Gras & Totohasina, 1995) is an interpretation of the conditional probability $P(A|B)$ as an implicit causal relationship; that is, the conditioning Event B is the cause and Event A is the consequence.

A very common misconception in probability is the confusion of independence with mutual exclusiveness (Díaz & Fuente, 2007). Mutual exclusiveness means that the intersection of two events is an empty set, whereas independence means that the probability of Event A given Event B simply equals the probability of Event A. Many define independence as “the two events have nothing in common,” thus confusing independence and mutual exclusiveness (Díaz & Fuente, 2007). Finally, some students confuse conditional probability with joint probability (Díaz & Fuente, 2007; Gras & Totohasina, 1995).
Research on students’ reasoning suggests the importance of different representations in solving binary hypothesis problems. For example, Zhu and Gigerenzer (2006) propose that students’ abilities to solve Bayesian tasks vary depending on the data being represented in terms of natural frequencies or probability. When the binomial hypothesis problem was presented in terms of probability to fourth, fifth, and sixth grade students, none of the students were able to estimate the Bayesian posterior probability. On the other hand, when the same information was presented as a natural frequency (e.g., rather than represent the probability as 0.07, state that “out of 100 women, 7 have cancer”), reasoning about conditional probability showed a steady increase from fourth to sixth grade, reaching an average level of 19%, 39%, and 53%, respectively, in two studies.

In summary, researchers who apply the deficit theory of risk education begin with the analysis of students’ perceptions (heuristics and biases) and then propose an intervention (e.g., the use of natural frequencies) in order to align the perceived risk with the actual risk (Figure 1).
Figure 1. Deficit (utility) model of risk. Adapted from Levinson, Kent, Pratt, Kapadia, and Yogui (2012).

Critiques of the Deficit Theory of RiskSimple Bayesian tasks similar to Eddy’s breast cancer problem can be approached using the deficit model because, within the context of the problem, there is an actual risk—or, to be more precise, an actual quantifiable risk. However, if the question is reframed as “How often should women over forty get mammograms?” or, even more specifically, “Should a particular person get a mammogram?”, it becomes ill-defined, meaning there is neither a clear solution nor a clear method of arriving at a solution. The deficit model is particularly inadequate when dealing with technoscientific situations such as epidemics, climate change, energy policy, or pharmaceutical research, where there is no consensus on how probability or impact should be calculated (Levinson et al., 2012; Lidskog & Sundqvist, 2013).
Even when problems are well defined, it is debatable whether individuals base their decisions simply on cognitive heuristics. In other words, when making risk-based decisions, are we really performing calculations at a varying level of complexity depending on our background in risk analysis? Paul Slovic, a veteran of heuristics research, began to doubt this several decades ago:

I recall, in the midst of this growing collection of heuristic strategies, wondering how people decided when it was safe to cross a busy street. Certainly they were not calculating probabilities and utilities or their summed products, and the known judgment heuristics did not seem to offer any insight. (Slovic, 2010, p. xx)

He instead proposes that any risk decision includes the affect heuristic, which is a cognitive process in which individuals use feeling (positive or negative) as a guide to evaluating risk.

Deficit theory also does not take into account that risk situations are “constructed by different histories, narratives, and experiences” (Levinson et al., 2012, p. 216). For example, Levinson and Rodd (2009) investigated pre-service teachers’ conceptions of risk related to the question of whether malaria is a major risk in travelling to West Africa. A student who had had an experience with malaria downplayed the risk; “what was seen as a major risk by one person was not perceived as a significant risk by another” (Levinson et al., 2012, p. 216).

Another problem with deficit theory is that it places expert knowledge before the knowledge of laypeople, regarding them as “poorly informed in comparison to the ‘precise’ and ‘scientific’ analyses of experts” (Beck, 2009, p. 12). Laypeople, however, “have the competence to contribute to discussions and decisions on risks since they concern them much more than scientific facts” (Lidskog & Sundqvist, 2013, p.94). Levinson et al. (2012) assert that “evolving models of interactions between experts and publics point toward a more reflexive expert perception of public concerns and a realization of the importance of public engagement” (pp. 216-217). Beyond public engagement, Gregory et al. (2012) call for the
meaningful inclusion of public knowledge into decision-making processes, focusing in particular on local and traditional knowledge characterized by the reliance on experience and observations rather than experimentation, often expressed in more holistic rather than reductionist fashion, and dealing with particular concerns and context-dependent situations.

Consistent with the value of public knowledge and decision making, Levinson et al. (2012) consider personal models in understanding of risk for two reasons:

1. Learning involves the modification of preexisting personal models in interaction with others, rather than learning being a process of replacing learners “wrong” thinking with models of “right” thinking and
2. It is critical to respect personal models because personal values (as expressions of personal preferences and ethical positions) and social and affective values are inextricable from making decisions. (p. 217)

It follows that risk should be taught and learned in an environment that creates opportunities “to make explicit values, experiences, and representations of those experiences and probabilities that foreground the decision-making process, and where probabilities can be judged in light of, and interact with, expressed values” (Levinson et al., 2012, p. 228). An inquiry-based approach can offer such an environment (Pratt & Yogui, 2010).

**Pedagogic Model of Risk**

For the purpose of exploring the pedagogy of risk, researchers involved in the Institute of Education’s TURS Project (Promoting Teachers’ Understanding of Risk in Socio-scientific Issues) developed a computer microworld called Deborah’s Dilemma (Levinson et al., 2011; Levinson et al., 2012; Pratt et al., 2011). In Deborah’s Dilemma, students were engaged in a narrative involving a fictitious person, Deborah, who suffers from a spinal cord condition. Based on the data about the side effects of a surgery and the consequences of not having the surgery, pairs of math and science teachers had to choose the best possible course
of action for Deborah. One of the outcomes of the research program was the development of the pedagogic model of risk (Levinson et al., 2012).

According to this model, probabilistic judgments lead to the estimation of risk but the judgments are informed by values, experiences, personal and social commitments, as well as representations (see Figure 2). This is in contrast with the utility model of risk, where values are separate from the probabilistic judgments and may only play a role in risk management (following an analysis of risk). Relevant findings from the study have been used throughout this literature review to outline the elements of the pedagogy of risk.

Figure 2. Pedagogic model of risk. Adapted from Levinson, Kent, Pratt, Kapadia, and Yogui (2012).

Elements of the Pedagogic Model of Risk

In this section, I present the existing research that supports and expands upon the Levinson et al. (2012) pedagogic model of risk. This will be followed by research on the
estimation of risk, with a particular focus on coordination between probability and impact. Finally, the role of context in the pedagogy of risk will be discussed.

**Probabilistic Judgments**

In terms of probability knowledge, there are several frameworks that describe probabilistic reasoning. The major frameworks mentioned in the literature are Core Domain of Probability Concepts (Moore, 1990), Probability Thinking Framework (Jones et al., 1997; Polaki et al., 2000), and Gal’s knowledge elements of probability literacy (Gal, 2004b, 2005). Moore (1990) describes the conditions that students need to satisfy in order to be able to move towards more difficult concepts such as conditional probability. These conditions are: 1) learning to discern the overall pattern of events and not attempt a causal explanation of each outcome; 2) recognizing the stability of long-run frequencies; 3) assigning probabilities to finite sets of outcomes and comparing observed proportions to these probabilities; 4) overcoming the tendency to believe that the regularity described by probability applies to short sequences of random outcomes; and 5) applying an understanding of proportions to construct a math model of probability and develop an understanding of some “basic laws or axioms that include the addition rules for disjoint sets” (Moore, 1990, p. 120).

One of the most comprehensive frameworks describing probabilistic reasoning is provided by Jones et al. (1997). The framework is divided into four constructs: 1) sample space, 2) probability of an event, 3) probability comparisons, and 4) conditional probability. The framework also recognizes four levels of reasoning: 1) subjective, 2) transitional between subjective and naïve quantitative, 3) informal quantitative, and 4) numerical.

Polaki et al. (2000) provide an extension of the Jones et al. (1997) framework. Their framework describes probabilistic thinking across five constructs: 1) sample space, 2)
probability of an event, 3) probability comparisons, 4) conditional probability, and 5) independence. The Polaki et al. (2000) framework has been used to explain requirements for understanding compound events in terms of the sample space and the probability of the event constructs (Nilsson, 2007). The Jones et al. (1997) framework, which serves as a basis for the Polaki et al. (2000) framework, was used by Langrall and Mooney (2005) to interpret the grade three students’ understanding of probability in Falk and Wilkening’s (1998) research.

According to Gal (2005), knowledge elements jointly contribute to people’s ability to comprehend, interpret, critically evaluate, and react to statistical messages. These elements go beyond the subject content knowledge to include literacy as well as critical skills. Gal’s (2004a) statistical literacy framework identifies knowledge elements such as literacy skills, statistical and probabilistic knowledge, mathematical knowledge, content knowledge, and the critical questions about data.

**Representations**

One of the biggest challenges for learners of risk is the issue of representations. The claim that the Bayesian problem is simpler when the probability is represented in terms of natural frequencies is made elsewhere (Cosmides & Tooby, 1996; Gigerenzer, 1994; Gigerenzer & Hoffrage, 1995). These researchers offer an evolutionary psychology explanation of why most people find Bayesian tasks represented using natural frequencies easier than others. According to this explanation, humans are “hard wired” to deal with natural frequencies rather than with probabilities.

In the Levinson et al.’s (2012) study, however, the choice of representation seemed to depend on the context. For example, when deciding whether Deborah should have surgery based on data about the success rate, a teacher claimed that, if they were arguing for the
surgery, they would represent the rate of failure in terms of probability ("less than a half of seventh"), whereas, if the recommendation was against the surgery, they would represent the data in terms of natural frequency ("four people") because it contains information on actual people impacted by the failure. The idea that natural frequencies carry more weight in representing impact is confirmed by Tim, another teacher in the Levinson et al.'s (2012) study:

I mean if you’re going to say “60 people died from this procedure,” is that enough to tempt someone to say “alright I’ll give that a go”? Ok that would look bad because 60 people is more impacting on you than one in 1000, one in 10,000. Those big figures will convince you, but I think “60 people died from this last year” convinces you in a different way, even though the figures, you know that’s where the one in 50,000 comes from. The way you present your data is very important to an individual. (p. 223)

Levinson et al. (2012) also documented that teachers made mistakes in calculating percentages:

In paired dialog, it was easy for teachers to miscalculate small percentage values into figures and proportions more commonly used in everyday discourse. Overall, this illustrates a common problem, where people find large numbers and low probabilities difficult to comprehend. It suggests the need to take care in designing materials about risk, possibly highlighting the need to support students and consumers in negotiating and interpreting the ways in which probabilities are represented. (p. 223)

In terms of representations of impact, Pratt et al. (2011) document “fuzzy qualitative descriptors” used by students to roughly calculate impact ("serious," “massive,” “bad,” “fine,” “big”) (p. 339). Qualitative representations of impact (outcomes) were similarly documented by the Levinson et al. (2012) study; all three pairs of teachers considered impact in deciding whether Deborah should have the operation using phrases such as “impact on her life,” “pain threshold,” and “prohibitively dangerous option” to describe impact.

In contrast with qualitative representations of impact, there is a lack of research on what quantification of impact looks like in the classroom. There is, however, empirical
evidence that quantification does not come easy. Pratt et al. (2011) state that there was no
opportunity for teachers to quantify impact:

At no point did any of the six teachers attempt to numerically quantify impact and
certainty [sic] in designing the task we provided no explicit encouragement to move
beyond fuzzy quantifications of how much additional pain might be caused by a
lifestyle decision. Perhaps because of the difficulties in quantifying impact, and to
some extent of making sense of the odds, we observed no attempts to quantify risk
per se in a formal way. (p. 339)

We can conjecture, however, that quantitative reasoning about impact will be
consistent with quantitative reasoning described by statistical literacy frameworks. According
to these frameworks, understanding of rational numbers, including the understanding of ratio
and proportion, is another domain of quantitative knowledge and is a necessary prerequisite
for performing at the highest level of statistical understanding (Watson & Callingham, 2003;
literacy is a hierarchical construct with proportional reasoning featured at its highest levels
(see Table 1). At the highest level, critical mathematical, students are required to use
“proportional reasoning associated with ratio and appropriate part-whole interpretations, the
ability to use rates in calculating costs” (p. 18).

Table 1

<table>
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<th>Statistical Literacy Construct</th>
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<td>Level</td>
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<tr>
<td>6. Critical Mathematical</td>
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<td>5. Critical</td>
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qualitative interpretation of chance, and appreciation of variation.

4. Consistent Non-critical
Task-steps require appropriate but non-critical engagement with context, multiple aspects of terminology usage, appreciation of variation in chance settings only, and statistical skills associated with the mean, simple probabilities, and graph characteristics.

3. Inconsistent
Task-steps at this level, often in supportive formats, expect selective engagement with context, appropriate recognition of conclusions but without justification, and qualitative rather than quantitative use of statistical ideas.

2. Informal
Task-steps require only colloquial or informal engagement with context often reflecting intuitive non-statistical beliefs, single elements of complex terminology and settings, and basic one-step straightforward table, graph, and chance calculations.

1. Idiosyncratic
Task-steps at this level suggest idiosyncratic engagement with context, tautological use of terminology, and basic mathematical skills associated with one-to-one counting and reading cell values in tables.

Adapted from Watson and Callingham (2003).

Proportional reasoning causes difficulty for many middle school (Lamon, 2007) and high school students. For example, Akatugba and Wallace (1999) studied students’ proportional reasoning in a physics class and found that students had difficulty performing mathematical operations that were not explicitly stated in the task. The conclusion of the study was that students’ understanding of mathematical processes involved in proportional reasoning was inadequate.

Values, Experiences, Personal, and Social Commitments
Students also must be aware that the collection, generation, and interpretation of data are influenced by social factors and are consequently value-laden (Pratt et al., 2011; Watson, 1997). In order to examine the social factors, students must be able to critically examine data (Gal, 2004a; Pratt et al., 2011). In addition, thinking about risk also involves decision making
that can function on an individual level, societal level, and within the intersection of these levels (Pratt et al, 2011).

The importance of critical evaluation of data is consistent with the consensus among educators stating that literacy should extend beyond a minimal subset of skills expected for all. According to Gal (2005):

increasingly the term literacy, when used as part of the description of people’s capacity for goal-oriented behavior in a specific domain, suggests a broad cluster not only of factual knowledge and certain formal and informal skills, but also a desired beliefs, habits of mind, or attitudes, as well as a general awareness and a critical perspective. (p. 42)

For the purpose of the critical evaluation of data, Gal (2004a) introduced a list of critical or worry questions which enable individuals to critically evaluate information provided. The critical questions include questions about reliability and the validity of data (Gal, 2004a, 2004b, 2005).

The students’ perception of reliability of data is an important critical element. There is evidence that some individuals associate reliability with disinterestedness. For example, Pratt et al. (2011) found that two participants in their study (Linda and Adrian) were suspicious of the surgeon who they thought may be “drumming up the business” (p. 340).

Levinson et al. (2012) found that students “recognize the role of trust and authority in giving meaning to the data” (p. 224). The authors reported that a participant (Linda) found the spine doctor’s recommendation reliable because he “knows more about it than the other people, and he’s seen more of these people” (Levinson et al., 2012, p. 224). The notion of trust in groups that are involved in measurement is evident in Kolsto’s (2001) study. Despite the fact that the students were sceptical of the power company’s risk evaluation and the
power company was marked as interested, the students accepted the company’s claims concerning magnetic field strength from different sources.

Besides the issues of reliability, there is an issue of content validity, which includes the questions of how the statement about data was derived, whether the claims are supported by the data, and whether additional information and interpretations are needed (Gal, 2004b). Kolsto (2001) provides evidence that students are quite vigorous in questioning the source of data but are less likely to question the validity which requires students to analyze the content of the source and evaluate the arguments presented in the document.

Research on affect heuristics also sheds light on the ways that individuals make decisions about risk. Slovic, Finucane, Peters, and MacGregor (2010), influenced by the dual processes theory (Kahneman & Frederick, 2002), suggest that human reasoning about risk consists of two cognitive systems: one is the experiential, intuitive system that helps us make quick assessments about the safety of a situation (“a gut feeling”), the other is the analytic system that helps us evaluate our thinking. Slovic, Finucane, Peters, and MacGregor (2010) do not want to fall into a trap of deficit theorists by favouring the analytic system over the experiential. According to recent research, affect that stems from the experiential system helps us to make decisions quickly in an uncertain and dangerous world:

We now recognize that the experiential mode of thinking and the analytic mode of thinking are continually active, interacting in what we have characterized as the ‘dance of affect and reason’ (Finucane et al., 2003). While we may be able to ‘do the right thing’ without analysis (e.g. dodge a falling object), it is unlikely that we can employ analytic thinking rationally without guidance from affect somewhere along the line. Affect is essential to rational action. (Slovic, Finucane, Peters, & MacGregor, 2010, p. 24)

An example of affect heuristics is the feeling of dread (Fischhoff et al., 1978), which has been shown to be a major predictor of public perception of risk for a wide range of
phenomena (Slovic, Finucane, Peters, & MacGregor, 2010). For example, the feeling of dread towards nuclear power has resulted in the view of nuclear power “as a technology whose risks are uncontrollable, lethal, and potentially catastrophic” (Slovic, Fischhoff, & Lichtenstein, 1982, p. 485).

**Estimation of Risk**

In contrast to the research on probability, there are no comprehensive frameworks for analyzing students’ estimation of risk, particularly the estimation that involves coordination between probability and impact. However, the research of Pratt et al. (2011) suggests that, in order to comprehend the coordination, students must have both algebraic and analytic geometry skills that will enable them to manipulate formulae and graph functional relationship between two variables.

Levinson et al. (2012) state that the participants in their study did not sufficiently coordinate between probability and impact; instead, the majority of discussion was based on personal attitudes of the group of teachers. The authors state that “while there was some discussion of probabilities, these only interacted with the decision on outcomes in a marginal way or provided insufficient background for a decision to be made” (p. 226). In addition, Levinson et al. state that:

there were relatively few instances where the teachers simultaneously balanced changes in lifestyle against the likelihood of the operation resulting in serious harm. This might have been a problem in the way the data were presented, but it was more likely that personal preferences were driving decisions irrespective of emerging evidence. (p. 228)

**The Role of Context and Content Knowledge in Pedagogy of Risk**

Pratt et al. (2011) ask whether context may impede students’ understanding of risk, drawing on examples from the previous studies which suggest that context may be
detrimental to the mathematical understanding of risk. Pratt et al. (2011) conclude that the understanding of risk is closer to statistics than mathematics and that the context is crucial. If we strip away context and reduce the task of assessing risk to the mathematical coordination between likelihood and impact, we can see that the meaning is lost. Also, the numbers (quantitative data) have to be viewed in context. Pratt et al. (2011) also consider the issue of who the decision maker is as an element of context. In other words, students will respond differently depending on whether they are making decisions about themselves or another person.

Data concerning risk and uncertainty are never decontextualized and comprehensive interpretation of data involving risk requires placing data in an appropriate context (Gal, 2005). Therefore, contextual knowledge is essential for risk analysis. For example, the analysis of risk of a nuclear power plant accident requires content knowledge about nuclear power plants. Understanding of risk contains many elements of mathematical reasoning (logical, probabilistic, and proportional reasoning); it also contains many elements of the quantitative reasoning in context (Mayes, Peterson, & Bonilla, 2012). According to the authors:

Quantitative reasoning in context (QRC) is mathematics and statistics applied in real-life, authentic situations that impact an individual’s life as a constructive, concerned, and reflective citizen. QRC problems are context dependent, interdisciplinary, open-ended tasks that require critical thinking and the capacity to communicate a course of action. (p. 10)

The following table compares mathematical reasoning and quantitative reasoning in context.

Table 2

Comparison Between Mathematics and Quantitative Reasoning

<table>
<thead>
<tr>
<th>Mathematics</th>
<th>Quantitative Reasoning</th>
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<tbody>
<tr>
<td>Power in abstraction</td>
<td>Real authentic contexts</td>
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Pratt et al. (2011) acknowledge, based on their study of math and science teachers, that reasoning about risk is highly contextualized. They differentiate between the context of the problem and the setting where reasoning takes place, namely reading, inquiry, and pedagogic setting (Monteiro & Ainley, 2003). An example of a reading setting is reading newspaper articles or advertisements, an inquiry setting is one in which an individual engages with data to solve the problem, and a pedagogic setting is the school setting where highly formal and mathematical ways to solve very specific problems are used (Pratt et al., 2011). It can be argued that, when solving problems, students can have different goals within each context.

Pratt et al. (2011) conjecture and show evidence that these three settings differ in the way participants use cognitive resources. They assert that cognitive resources most readily used in the reading setting are affective (emotional) responses followed by the understanding of context. In the inquiry setting, understanding of the problem context takes precedence over mathematical and statistical knowledge, though this knowledge is also important. Finally, the authors conjecture that, in the pedagogic setting, which is intended to teach and assess
particular ideas, statistical and mathematical ideas are prioritized, whereas affective resources are less likely to be drawn upon.

One of the prerequisites for understanding of risk is content knowledge (e.g., in order to be familiar with risk of nuclear power plants accidents, we should have relevant knowledge about nuclear power). However, possession of content knowledge does not guarantee that the knowledge will be used in risk assessment. For example, Levinson et al. (2012) state that:

there were many opportunities in the microworld for the teachers…to make use of relevant scientific knowledge in helping to evaluate risk, but none chose to do so, reflecting other accounts, where scientific knowledge and information are either marginal or irrelevant to lay decision making. (p. 228)

**Teaching Risk in the Classroom**

There is a lack of classroom studies of students’ understanding of risk; the studies that do exist stress the importance of treating risk-based decision making as a complex enterprise. The importance of the complexity of decision making is highlighted by Monteiro and Ainley (2003) in their study of student teachers who drew on four distinct resources: mathematical knowledge, contextual knowledge, affective responses, and personal experiences. The authors found that “if attention is focused exclusively on one of these sources, then the judgment may be distorted” (as cited in Pratt et al., 2011, p. 338).

In order to create a classroom environment conducive to the complex view of risk, Kolsto (2006) suggests that students need “easy access to an appropriate range of information and viewpoints” (p. 1711). For example, in Kolsto’s study of high school student decision making related to electrical power lines, many students were only drawing their conclusions based on research-related information. Kolsto (2006), citing Aikenhead (1985), suggests that
if we want students to draw from wider domains (including values), we need to include tasks in which students are confronted with this information.

**Summary: Pedagogy of Risk**

In summary, a comprehensive pedagogy of risk should embrace complexity of the concept of risk as well as human risk-based decision making. Research supports the claim that classroom instruction needs to be inquiry-based and embrace students’ experiences, beliefs, and values (Pratt et al., 2011; Levinson et al., 2012). Based on students’ risk-based reasoning, the goal of the pedagogy of risk ought to be the articulation of pedagogical strategies needed for teaching and learning and finding a place for the instruction within the mathematics curriculum. However, in order to articulate the pedagogical strategies, there ought to be more research on how students reason and make decisions about risk in the mathematics classroom setting.
Chapter Three: Methodology

I applied a qualitative case study approach as I explored the teaching of risk in two grade 11 classrooms that were using an inquiry-based learning approach to pedagogy. This chapter begins with a justification of my selection of a qualitative case study methodology for conducting research in the classroom, followed by my reasoning for the use of inquiry-based learning. I then outline the selection of the school, teachers, and participants, as well as the chronology of research, including the initial interviews with teachers, initial assessment of students, inquiry-based activities, final assessment, and final interviews with teachers. The chapter concludes with a detailed description of methods used for data collection and analysis, and also the ethical considerations relevant to my research.

Classroom Research in Mathematics Education

Experimental has been a dominant approach to research on mathematics teaching and learning. Because of prevalence of experimental research, I will outline its methodological foundations and characteristics. The central concept of the experimental approach is causality, the idea that certain pedagogical choices (particular teaching method or teaching instruments) will lead to a different educational outcome (e.g., “better” understanding of risk).

The experimental method, which mimics the experimental method in natural sciences, manipulates “certain influences, or variables, and observes how the behaviour is affected or changed” (Best & Kahn, 2003). The experimental approach derives its understanding of causality from the regularity concept of causality as proposed by David Hume. He claimed that causality can neither be determined a priori nor observed directly; instead, we observe the regular occurrence of two events and then, through the experimental method, we infer the
causal relationship (Hume, 1993). According to Hume, one of the necessary, though not sufficient, conditions for inferring causality is regularity or constant conjunction between the cause and the effect—“every object like the cause, produces always some object like effect” (p. 129). Applying Hume’s ideas to educational research, we cannot infer causality from a single case; under controlled circumstances, the effect of an intervention has to regularly occur with the cause.

From the 19th century onward, Hume’s ideas about causality were merged with the statistical method which engendered the variance theory of causation that uses statistical methods to study “systematic effect” (Maxwell, 2004). For example, in educational research, in order to claim causality between an intervention and student understanding, we might perform a classroom intervention with the component A (e.g., computer visualization) and observe B (e.g., average scores over 90%). We then do a classroom intervention with a control group without A and observe B (average scores under 40%). Given a sufficiently large sample (consistent with statistical theory) we conclude that A caused B.

In order to argue for the legitimacy of non-experimental research, Maxwell (2004) has advocated for a different view on causality. First of all, Maxwell, following the critical realist tradition in social science, has argued that one can indeed observe causality from single cases. He defends a process-oriented approach to causality in which causal mechanism can be unearthed by looking at a single case and explaining the phenomena without breaking it down into dependent and independent variables. In this process, context plays a very important role. For example, “the context within which a causal process occurs is, to a greater or lesser extent, intrinsically involved in that process, and often cannot be controlled for in a variance-theory sense without misrepresenting causal mechanism” (Sayer, 2000,
p.114, as cited in Maxwell, 2004). In other words, context is not just noise or something that makes generalizability more difficult; rather, it plays a fundamental role in the explanation of educational phenomena. Maxwell (2004) concludes that:

> to develop adequate explanations of educational phenomena, and to understand the operation of educational interventions, we need to use methods that can investigate the involvement of particular contexts in the processes that generate these phenomena and outcomes. (p. 6)

Another important element in understanding causal explanation is related to the meanings ignored in variance theory of causality (Bruner, 1990; Maxwell, 2004). Meanings, beliefs, values, and intentions held by participants in a study are essential to study of causal mechanisms (understanding of intentionality). Also, we cannot ignore social science traditions that focus on meaning (interpretive dimensions of social life). The main premise of the process-oriented causation argument is that causes can be “observed.” In other words, an educational researcher does the intervention and he or she “observes” that A has caused B. Since what is observed depends on the theoretical lens one is using, the term “interpretation” is more appropriate than “observation”—but if we talk about interpretation, how can we interpret causation from a single case? How much weight does the interpretation hold in terms of defending a claim (e.g., “I did an intervention, and I am interpreting it as that the intervention caused a shift in understanding”)? The problem is that there are always rival interpretations and we have to explain and discriminate between counter-interpretations of causal relationships which weaken our arguments for causality.

**Case Study Research**

One solution to this problem is to move away from the idea of causality and introduce plausibility. Bruner (1990) posed a rhetorical question of whether plausible interpretations are not “preferable to causal explanations, particularly when the achievement of a causal
explanation forces us to artificialize what we are studying to a point almost beyond recognition as representative of life” (p. xiii).

Following Bruner, rather than focus on causality or the determination of ways that pedagogical decisions cause a shift in students’ thinking, I used the qualitative study approach to describe teaching and learning of risk in the classroom setting.

Case study is a “way of organizing social data for the purpose of viewing social reality” (Best & Kahn, 2003). Using a case study approach enables the researcher to “uncover the interplay among significant factors” that characterize the case (Merriam, 1998, p. 108). In addition, “a case study design is employed to gain in-depth understanding of the situation and meaning for those involved” (p. 19). My research is a case study consisting of two cases: two different grade 11 mathematics classrooms.

Research Setting and Participants

The first research setting was Dale Academy, an all-boys private secondary school following the International Baccalaureate curriculum. Every student at the Dale Academy had access to many educational resources, including laptop computers and wireless Internet. The reason why this school was chosen was to be able to see how risk pedagogy can be approached in settings in which there is no lack of resources. The grade 11 class was chosen because the International Baccalaureate probability and statistics unit was a good place for teaching and learning about risk. In order to have a greater diversity of participants, the second school was St. Hubertus Secondary School, a co-educational school with no direct access to laptops and no wireless Internet access. I did most of the teaching in the study—the two teachers, Breanna and Clarissa, were there to help me plan the lessons, observe them, and assist me with the logistics and classroom management. Thus, the case study centres on
the students and me, whereas the role of the classroom teacher was not explored in the study.

The detailed description of settings and participants is given in the findings section.

**Inquiry-Based Learning Approach**

In this section, I describe the inquiry-based learning approach (IL) and explain why it is appropriate for my study. As mentioned in the literature review, students’ risk-based reasoning should be rich and complex and involve not only thinking about mathematics and content knowledge but also personal beliefs and experiences (Pratt et al., 2011). IL is consistent with the above statement because, in IL, “students learn content as well as discipline-specific reasoning skills and practices (often in scientific disciplines) by collaboratively engaging in investigations” (Hmelo-Silver, Duncan, & Chinn, 2007, p. 100).

Inquiry-based learning involves authentic tasks that enable students to engage with the topic of inquiry. There are different views on what makes a task authentic (Levinson et al., 2012), but for the purpose of this thesis, I follow the distinction made by Murphy et al. (2006) between cultural authenticity and personal authenticity. They assert that cultural authenticity is present when students engage in a common social issue, whereas personal authenticity refers to an issue of importance to an individual student.

The Ontario mathematics curriculum is consistent with the goals of IL. The focus of the curriculum is development of students’ inquiry and problem-solving skills in an authentic setting:

Using a variety of instructional, assessment, and evaluation strategies, teachers provide numerous opportunities for students to develop skills of inquiry, problem solving, and communication as they investigate and learn fundamental concepts. The activities offered should enable students not only to make connections among these concepts throughout the course but also to relate and apply them to relevant societal, environmental, and economic contexts. Opportunities to relate knowledge and skills to these wider contexts – to the goals and concerns of the world in which they live –
will motivate students to learn and to become lifelong learners. (Ontario Ministry of Education, 2005)

Related research literature highlights the many ways in which the elements of IL are elucidated differently although, in essence, they are similar (Bybee et al., 2006; Hmelo-Silver, Duncan, & Chinn, 2007; Marshall & Horton, 2011). I draw upon the 5 E Model (Bybee et al., 2006) in which IL consists of five steps: 1) engage, 2) explore, 3) explain, 4) elaborate, and 5) evaluate. While presented linearly, the five steps do not always proceed chronologically and each of them may contain the teacher’s help and guidance.

The engagement stage consists of an activity or activities in which students engage in an issue which is either socially or personally authentic. In the exploration stage, students collaborate through an authentic task and begin to clarify their understanding of major concepts. Students are involved in the explanation stage when they construct concepts and processes about which they are exploring and learning. Finally, the elaboration activities challenge students to apply what they have learned to a new situation, and evaluation involves both students’ and teachers’ assessment of progress for the purposes of informing instruction (Bybee, et al., 2006).

**The Task: Safety of Nuclear Power Plants**

Preparation for the research coincided with the events following the Fukushima Daiichi nuclear power plant accident in Japan in the first half of 2011. Given the public concern as well as the media coverage of this tragic event, the context of nuclear power plant safety seemed to be both suitable and relevant for the IL lessons because students were more likely to be familiar with the event, make a connection between impact and risk, and be motivated to engage in the classroom activity (intervention) following the assessment. In other words, there were grounds for both cultural authenticity (i.e., the impact of nuclear
power plant accidents on the society) and personal authenticity (i.e., concern for personal safety).

The IL module started with an initial assessment of the student understanding of risk and knowledge of the Fukushima accident in order to engage students in the issue. The initial individual written assessment consisted of two questions setting the context of the issue. The first question was:

Do you agree or disagree with the following statement? Explain your reasoning. “There have been around 500 nuclear power plants built since the 1950s. So far there have been only three significant nuclear power plant accidents. This makes nuclear power relatively safe compared to other means of generating power.”

The purpose of the initial assessment was to show evidence that students possessed knowledge about impact prior to the instruction and to investigate language the students used when talking about impact. In addition, I wanted to investigate whether there was any evidence for the coordination between likelihood and impact as discussed by Pratt et al. (2011).

The second question consisted of two parts. First, the students were asked to write a paragraph on what they know about the accident. Their responses were then marked on a scale of 0 to 3 corresponding to the content of their answer (as described in the data analysis section as well as the findings). The second part of the question was: “What is your opinion on safety of nuclear power plants and how did the Fukushima incident influence your thinking?” The purpose of the question was to give students more opportunity to consider reasoning about risk in terms of probability and impact as well as to gauge their personal values, experiences, and personal and social commitments. The initial assessment was done during class and took around 30 minutes to complete; it is presented in Appendix C.
Following the initial assessment, there were 3 hours and 45 minutes of instruction (over the three 75-minute periods) on determining the empirical probability of nuclear power plant accidents. The activity started with a 75-minute lecture that defined key terms: probability, theoretical probability, and empirical probability.

Following the introduction, there was a 75-minute group activity (full period) with the following objectives: 1) to critically evaluate the sources of data provided; and 2) to estimate the empirical probability. The activity was specifically designed to contain the “explore,” “explain,” and “elaborate” elements of the 5 Es. The students were given a worksheet (Appendix D) in which they were presented with four websites to use as potential data sources. The websites contained nuclear power plant accident data and could be easily accessed with laptops. The websites were:

- World Nuclear Association (Appendix E1) – an organization representing the interests of the nuclear energy industry
- Greenpeace (Appendix E2) – an environmental activist group, giving a comprehensive list of incidents and accidents
- Datablog (Appendix E3) – the statistics blog from the *Guardian*
- Ecocentric blog (Appendix E4) – the environmental blog from *Time* magazine

I chose to give students specific websites rather than having them freely explore the Internet because by selecting from a shared set of websites, I was able to gain insight into the reasons why they picked one over the other.

After deciding which website to draw data from, students were instructed to estimate the probability of a nuclear power plant accident. Following the activity, the groups presented their findings to the class; this took approximately 75 minutes (one full period). The group presentations had the potential to contain the “explore,” “explain,” “elaborate,” and “evaluate” elements of the 5 Es.
Following the first activity, the second group activity (also 75 minutes) was completed and involved interpretation of data including likelihood and impact. The objective of the activity was to introduce students to the assessment of the impact, both qualitative and quantitative, and the coordination of the likelihood and impact, and to present them with the idea that the assessment may be value-laden. The activity is presented in Appendices F1 (Dale Academy) and F2 (St. Hubertus). In terms of the five Es proposed by Bybee et al., it contained the elements of “explore,” “explain,” and “elaborate.” This was followed by the presentation of data (75 minutes), containing the elements of the last four Es. Throughout the group activities, I was a facilitator assisting in student learning and using direct instruction to clarify certain points—the direct instruction was given to either the groups or the whole class.

**Data Collection**

Data collection for the first school started in March of 2011, with the four half-hour semi-structured interviews with the teacher in order to prepare for the lessons. These interviews were audio-recorded and helped me plan the activities in terms of choosing an appropriate class, duration of the activities, and the time period in which I could do the data collection. This data informed the IL activities but was not directly used in data analysis. All of the lessons were video-recorded; a camera captured the whole class and each group was video-recorded. In addition, student-written work from the initial assessment questions, handouts, and the construction paper given to each group for the activities was collected. I also kept field notes during the activities. This was challenging since I was also facilitating the lessons, and did not result in a rich and consistent data source. However, after each lesson, I recorded a reflection on each lesson and a short (5 minutes) debriefing with the
teacher that was audio-recorded. The debriefing consisted of the teachers’ assessment of the lesson, mostly their comments on the student engagement and on the logistics for the next activity. This data was used to make conjectures about the difference in engagement between the two groups. At the culmination of the series of lessons, I had an hour-long semi-structured interview with each teacher about her reflection on the activities (Appendix Q) as well as on her background as a teacher. These data were used to create a background of the teacher and also to make conjectures about the engagement differences between two groups.

Preparation for the data collection at Dale Academy began in March of 2011. The data collection began and ended in May of the same year. Preparation for the data collection at St. Hubertus Secondary School began in early September 2011. The second data collection, at St. Hubertus, began in October and ended in November of 2011 and had the same structure as the first data collection.

Data Analysis

In this section, I give a detailed description of data analysis for the initial assessment, the first nuclear activity (group activity and group presentations), the second nuclear activity (group activity and group presentations), and, in the case of St. Hubertus, the final assessments. I also describe how the teacher interviews were analyzed.

For the qualitative data analysis I used codes which are “tags or labels for assigning units of meaning to the descriptive or inferential information compiled during a study” (Miles & Huberman, 1994, p. 56). I used three types of coding, namely open coding, axial coding, and selective coding (Strauss, 1987). Open coding is involved in the initial stage of the analysis of the transcribed data. In this stage I identified the themes that emerged either from reading the transcripts or a priori from the literature review. The second type is axial
coding, in which the researcher looks at the connection between the existing themes organized in the first round of coding. Finally, in the selective coding, researchers look at instances that illustrate themes, as well as performing comparisons and contrasts between themes.

**Initial Assessment**

For the first question, I started with open coding which involved coding each student’s response based on their language and reasoning about impact, their language and reasoning about probability, and other ways of reasoning about impact. The codes were designed a priori from the literature on individuals’ reasoning about probability and impact, more specifically Levinson et al. (2012) and Pratt et al. (2011) study. I then counted the number of students who agreed, disagreed, or neither agreed nor disagreed with the statement. For the purpose of axial coding, which involves relationships between different themes, I tallied how many arguments were based on impact and how many on probability, thus exploring how these two categories are related. Finally, after selective coding, I created the themes of language about impact and reasoning not based on impact, together with representative quotes describing each category and their relationship to whether students agreed or disagreed with the statement. I included the table containing only names of students who based their argument on impact and stating whether they agreed or disagreed with the original statement. The summary tables for Dale Academy and St. Hubertus Secondary School are presented in Appendices H and L respectively.

In order to analyze the first part of the second question, namely what students knew about the Fukushima accident, the marking scheme was created. Based on the knowledge of
the Fukushima Daiichi accident, I decided that the complete answer should contain the following three elements:

1. Earthquake (tsunami) hit Japan.

2. The power plant’s cooling system was damaged, causing the meltdown.

3. The population as well as the environment were affected.

For the last element, I decided not to be more specific about what is meant by population and the environment being “affected” (e.g., health and environmental consequences) for two reasons. The first one is that, to this day, there is no complete information on the impact of the Fukushima accident due to political and logistical reasons as well as the uncertainty of the modern science about the effect of the radiation on the planet’s ecosystem. The second reason is that the scientific knowledge about the scope of the accident was different in the spring of 2011 when the data at Dale Academy were collected compared to the fall of 2011 when the data at St. Hubertus Secondary School were collected. For each element, a student was awarded one point. Partial marks were also awarded in increments of 0.5. I then included the scores in the spreadsheet and calculated the mean and standard deviation of the responses to get a quantitative sense of the overall scores.

For the second part of the second question, which discussed the students’ beliefs about the safety of nuclear power plants, I originally counted the number of students who believed the nuclear power plants were safe and the ones who thought they were not. I revised the counting scheme when I realized that many students used qualifying statements to express their opinion (e.g., stating that the nuclear power plants are safe in “stable” areas). The codes—reasoning about probability, reasoning about impact, values, experiences, personal, and social commitments—were also determined a priori based on the relevant
literature (Pratt et al., 2011; Levinson et al., 2012). In the findings section, I listed either typical responses or the responses that best illustrate elements of the Levinson et al. (2012) pedagogic model of risk. For example, Marco’s statement that he was in China during the accident was not typical, but it serves to illustrate an element of the Levinson et al. (2012) pedagogic model of risk, namely personal experiences.

In the findings section, I then compare the answers to the first question to the second question and include typical responses. The complete table of students’ responses to the second question includes their score on the first part, whether they found the nuclear power plants safe and whether they used impact and probability in their arguments. I then include the summary of their responses. The summary tables describing the results from Dale Academy and St. Hubertus Secondary students are included in Appendices I and M respectively.

**The First Nuclear Power Plant Activity**

The first part of the activity involved students dividing into groups around which website out of four choices should be used in estimation of probability. I analyzed each group’s video data including their presentations. In addition, I analyzed the student work on the construction paper as well as some written responses on individual sheets (some students did not record anything on their own sheet; instead they found that the responses on the construction paper were sufficient).

The code that was determined a priori was student judgment of reliability which came from the review of literature (Kolsto, 2001; Levinson et al., 2012). I started the analysis with open coding the construction paper data and individual responses. I then noticed that the websites that students chose were not necessarily the ones that they found most reliable.
Based on student responses, I added the code titled “the judgment besides reliability”, and more specifically, “presentation of data”. I did not go beyond the open coding of the written data; instead, I started to analyze each group video. The progression of video followed the order of answers on the construction paper. I transcribed each video verbatim. Through axial coding, followed by selective coding, I ended up dividing the findings into two themes, namely “deciding on reliability” and “choosing the website.” I included the representative and illustrative quotes mostly from the construction paper and students’ presentations. I also included an exchange between two students illustrating the importance of both numerical and qualitative information of making sense of the data. The summary tables listing each group’s choice of the most reliable website, the data source, and the least reliable website, together with reasons for their decisions, are included in Appendices J and N.

The second part of the first nuclear activity was concerned with the estimation of empirical probability. Again, I started with the open coding of the construction paper data including the a priori codes obtained from the literature review, namely probability judgment, decision based on probability, and representations of probability (Levinson et al., 2012). Through reading the transcript I noticed that the students were using reasoning about rational numbers and included it in the coding scheme. I then transcribed the group data and corresponding presentation data. Through axial and selective coding I organized the findings chapter into two sections: estimating empirical probability and decisions based on probability. Besides the quotes, I included episodes involving exchanges between different group members that were illustrative and representative of themes. In addition, I included a photograph of a group’s work on the construction paper to further illustrate the point that the
students’ beliefs took priority over calculations in deciding on the safety of nuclear power plants.

**The Second Nuclear Power Plant Activity**

I started with an open coding of the group work on the construction paper. The a priori quotes based on the literature review included language and representation of impact, coordination of probability and impact, and content knowledge (Levinson et al., 2012; Pratt et al., 2011). After analyzing the construction paper data, I added the role of beliefs and values and rational number reasoning, which was further divided into proportional reasoning, reasoning about ratio, and reciprocal reasoning. I then transcribed the video data and presentation data. Through axial and selective coding I ended up with themes of definition, assessment, and comparison of impact in which I described qualitative and quantitative representations of impact as well as the role of content knowledge. I included episodes that were either representative of the data or served to illustrate the Levinson et al. (2012) pedagogic model of risk. In order to visualize the episode in which students discuss the structure of the society, I also included a diagram depicting the relationship between government, environment, and people as perceived by a group.

**Final assessment**

In the case of Dale Academy, the students’ opinions about the safety of nuclear power plants were gathered from the second presentation and the data they included on construction paper. During the data collection at St. Hubertus, I decided to gain better insight into their opinion by having them answer the first question from the initial assessment. Their answers are included in Appendix P.
**Interview with the Teacher**

Interviews with the teachers were open coded based on their background, knowledge of probability, and opinions on student engagement. The interviews were used to create a background of the teacher in the findings section. I also used the interviews to create the profile of both schools and classrooms as described in the findings section.

**Ethical Considerations**

The ethical review process for interviews was completed and ethical protocol was accepted by the University of Toronto Ethics Committee. To protect the anonymity of participants, pseudonyms of all students, teachers, and schools were used. Furthermore, the school board and geographical location were not identified in order to help ensure confidentiality. All participants in the study gave written informed assent (Appendix G1). Similarly, the parents of the participants gave written informed consent forms to complete (Appendix G2), as did the teachers (Appendix G3).
Chapter Four: Findings

In this chapter, I will present findings of teaching risk literacy in two different settings: Dale Academy, an all-boys private secondary school, and St. Hubertus Secondary School, a coeducational religious school. The section starts with the description of the case of Dale Academy. I present the background of the school, students, and teacher, as well as the description of the course and the physical characteristics of the classroom. I then move to an outline of students’ reasoning about the nuclear power plant activity which is divided into two parts: assessment of likelihood and the coordination between likelihood and impact. The same sequence is then repeated for the case of St. Hubertus Secondary School.

Case One: Dale Academy

Dale Academy is a prestigious all-male private school in a major urban area in Canada. It prides itself as a school with a long tradition of academic excellence. Most of the students come from families with a high socio-economic status. In the year of my research, there were approximately 1000 day students and 110 boarders. The secondary school consists of five grades: year 1 (corresponding to the Ontario public system’s grade 8), year 2 (grade 9), foundation year (grade 10), and the International Baccalaureate Program’s years 1 and year 2 (grades 11 and 12). Although there is limited diversity in terms of socio-economic status, the student body is fairly diverse in terms of students’ cultural and national backgrounds and first language. Many of the boarding school students come from Asian, Middle Eastern, and European countries.

Because of the school’s academic reputation, most of the students are university-bound; after graduation, students enter university programs in Canada and abroad. Mathematics instruction in the International Baccalaureate Program is divided into three
levels depending on teacher judgments of students’ aptitude: mathematics studies (lowest level), standard level, and the higher level.

Resources available to students were commensurate with the profile of the school. There was mathematics help available every day before and after school. There was a campus learning centre matching students with one-on-one tutoring if and when needed. Every student had his own laptop computer (connected to the school’s wireless network) and a graphing display calculator (GDC). Almost every classroom was equipped with interactive white board technology. Students were required to have a school email address and use it in everyday communication regarding school-related issues. Teachers reported experiencing pressure to gear the instruction towards exam preparation—they often interjected during regular lessons to review potential exam topics. The final exam was created by the faculty whereas the final exam before graduating was an external exam designed and scored by the International Baccalaureate examination board and their employees. This added additional pressure and served as external motivation to students.

Students

There were 24 students in the classroom (see Table 3). They were enrolled in the first-year International Baccalaureate senior program (IB1), which corresponds to grade 11 in the public system, implying that the students were, on average, 16 years old. The mathematics course was a year-long standard level IB1 course in session from September until June and met every other day for either 50 or 75 minutes. I started with classroom visits in early April and ended in late May. The students were preparing for the final International Baccalaureate exam which is administered to each student at the end of the school year in June.
Following initial assessment there was a two-hour-and-fifteen-minute group activity on determining the empirical probability of nuclear power plant accidents. As outlined in the methods chapter, the activity was introduced with a 75-minute lecture on the definitions of terms: probability, theoretical probability, and empirical probability. Following the activity, the groups presented their findings, which took 75 minutes. The second group activity lasted 75 minutes and involved determining the safety of nuclear power plants using data including likelihood and impact. The objective of the activity was to introduce students to the assessment of the impact, coordination of the likelihood and impact, and the idea that the assessment may be value-laden.

Table 3

*The List of Student Participants at the Dale Academy*

<table>
<thead>
<tr>
<th>Student</th>
<th>Pseudonym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 1</td>
<td>Blair</td>
</tr>
<tr>
<td>Student 2</td>
<td>Jared</td>
</tr>
<tr>
<td>Student 3</td>
<td>Luis</td>
</tr>
<tr>
<td>Student 4</td>
<td>Aaron</td>
</tr>
<tr>
<td>Student 5</td>
<td>David</td>
</tr>
<tr>
<td>Student 6</td>
<td>Samir</td>
</tr>
<tr>
<td>Student 7</td>
<td>Cai</td>
</tr>
<tr>
<td>Student 8</td>
<td>Marco</td>
</tr>
<tr>
<td>Student 9</td>
<td>Sasha</td>
</tr>
<tr>
<td>Student 10</td>
<td>Anjun</td>
</tr>
<tr>
<td>Student 11</td>
<td>Luca</td>
</tr>
<tr>
<td>Student 12</td>
<td>Andrew</td>
</tr>
<tr>
<td>Student 13</td>
<td>Zu-Zhang</td>
</tr>
<tr>
<td>Student 14</td>
<td>Federico</td>
</tr>
<tr>
<td>Student 15</td>
<td>Mario</td>
</tr>
<tr>
<td>Student 16</td>
<td>Adam</td>
</tr>
<tr>
<td>Student 17</td>
<td>Alex</td>
</tr>
<tr>
<td>Student 18</td>
<td>Lee</td>
</tr>
</tbody>
</table>
**Teacher**

Breanna was a high school mathematics teacher in her forties. She lived on campus with her husband, also a teacher at the school, and her two children. In the year of the study, Breanna had been at the school for five years and was mostly teaching IB1, IB2, and some foundation year classes. She held a bachelor’s degree in mathematics, a master’s degree in education, and a teaching certificate in mathematics education. Prior to teaching at Dale Academy, she was a mathematics teacher in the public secondary system. She considered herself comfortable in both pedagogical and mathematical content knowledge. The area of mathematics that she found most challenging as a teacher and a learner was probability.

**Initial Assessment**

The purpose of the initial assessment was to test whether students possessed intuitions about impact and whether they were coordinating between probability and impact. In addition, as mentioned in the methodology section, students were asked to describe their knowledge of the Fukushima accident and their beliefs about nuclear power. During the initial written assessment, students were given a question concerning the safety of nuclear power plants as follows:

Do you agree or disagree with the following statement? Explain your reasoning.

“There have been around 500 nuclear power plants built since the 1950s. So far there have been only three significant nuclear power plant accidents. This makes nuclear power relatively safe compared to other means of generating power.
Language About Impact

Out of nineteen students who completed the initial assessment, twelve students disagreed with the statement, five agreed, and two neither agreed nor disagreed. Eight out of nineteen students made arguments based on impact contrasting it with the likelihood of information from the question. For example, Andrew wrote:

No, you don’t know how drastic a nuclear accident is to another power plant accident (of a different form) so you cannot say which is safer. There may be few nuclear accidents, but they may be much more devastating than lots of other power plant accidents.

From the above statement, we can interpret the phrase “much more devastating” to refer to the impact of the event. Clint alluded to the fact that the context of the question (i.e., nuclear power plant safety) has made him consider other factors beyond probability in answering the question. He wrote: “I suppose it depends on the extent of the damage of the accidents; however, if it was another situation and 3 of every 500 created a problem I would claim it to be relatively safe.”

Although seven out of eight students who made statements based on impact disagreed with the statement, Adam used impact to express his agreement with the statement by stating that “the dangers of coal to the environment are far worse than the dangers of nuclear energy.” Among the phrases and words the students used to refer to impact were: ramifications, big deal, drastic, devastating, scale, extent. The table in Appendix H gives the summary of language used to refer to impact by the students who used impact as a part of their argument.

Reasoning Not Based on Impact

Out of the remaining four students who disagreed with the statement, two students thought that the probability was still too high. For example, Marco wrote:
3/500 = 0.6%
I disagree because having 3 incidents out of 500 plants, the probability of an accident is 0.6% which is still pretty high, as a method to be considered as a safe way of everything should be in the 0.00’s % range.

Five students who agreed with the statement argued solely on the probability. For example, David agreed because “500 plants functioning 24/7 with a large work force having only 3 significant accidents is safe.” Based on the initial assessment, there is evidence some students possessed intuition that the assessment of risk should be based on both probability and impact.

The purpose of the second question was to create a situation in which students were likely to think about an impact and see whether they would invoke probability. In addition, I wanted to know students’ opinions on nuclear power plants. The question consisted of two parts (complete assessment in Appendix C). The students were first asked to write a paragraph on what they know about the accident. The second question was: “What is your opinion on safety of nuclear power plants and how did the Fukushima incident influence your thinking?” In order to analyze the first part of the question, the marking scheme was created. I decided that the complete answer should contain the following three elements:

1. Earthquake (tsunami) hit Japan.
2. The power plant’s cooling system was damaged, causing the meltdown.
3. The population as well as the environment were affected.

For each element, a student was awarded one point. Partial marks were also awarded.

Overall, 20 students participated in this assessment. The mean score was 2.2, with the standard deviation of 0.5, which means that, in general, the students knew about the accident. The lowest mark was 0.5 and the highest was 3. The summary of the student scores and exemplars in each category is given in Table 4.
Table 4

*Dale Academy Student Scores on the Second Question with Exemplars for Each Entry*

<table>
<thead>
<tr>
<th>Score</th>
<th>Number of students</th>
<th>Exemplar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>“Some nuclear plants blew up in Japan.”</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>“An earthquake disrupted the power plant, causing the cooling water in the reactor core to drain out, which lead to a meltdown in the core (caused by a tsunami)”</td>
</tr>
<tr>
<td>2.5</td>
<td>8</td>
<td>“An earthquake damaged the cooling mechanism which forced the government to pump seawater into the reactor after huge amount of radiation.”</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>“The tsunami damaged the Fukushima reactor in Japan, causing the release of radionuclides into a large area (radiation). The radionuclides include Cs-154 and Ra-124 which have long half-lives. These affected the environment and population, causing potential harm/change to general population.”</td>
</tr>
</tbody>
</table>

Non-integer scores mostly occurred in situations where certain facts were implicitly but not explicitly stated. For example, from Table 4 above, the exemplar for the score 2.5 mentioned that there was a huge amount of radiation, which implies the harm for the general population and the environment, though it does not explicitly state it. On the other hand, the exemplar for the score of 3 does include that it “affected the environment and population, causing potential harm/change to general population.” Only six out of twenty students made references to the accident being harmful to the population and the environment. The second part of the question dealt with the students’ opinions about the safety of nuclear power plants. Out of 20 students, five stated that nuclear power plants were safe and that the Fukushima accident did not change their opinion, 12 students stated that they were safe but with a
qualifying statement, one thought they were unsafe, and the opinions of two students were unclear from the answer they wrote.

Out of five students who thought that nuclear power plants were safe, four students mentioned impact in their statements and three students mentioned likelihood.

For example, David wrote about both impact and likelihood:

Nuclear power is unbelievably safe compared to other forms of power generation. There have been only three major incidents in nuclear power generation: Fukushima, Chernobyl, and Three Mile Island. All three were preventable, for the most part (except for Chernobyl) the radiation was contained and a minimal number of people died.

The student’s opinion about likelihood (i.e., the likelihood being low) can be inferred from the statement that “there have been only three major incidents in nuclear power generation.” On the other hand, the impact can be inferred from the claim that “the radiation was contained and a minimal number of people died.” Fahad also wrote about likelihood and impact:

I have always felt that nuclear power plants are relatively safe- over the history of nuclear power, I can only think of Three Mile Island and Chernobyl as examples of nuclear failures and both were more human than mechanical error. That being said, it’s undeniable that the threat of a nuclear disaster, however unlikely is terrible. The Fukushima incident has had negligible effect on my thinking.

The student thinks that risk of failure is not intrinsic to the nuclear power plants but related to human error.

Similarly, Federico also thought that risk is not intrinsic to the system. However, in the case of Fukushima, he attributes it to the external causes (earthquake):

Nuclear power plants aren’t especially threatening if there is a good plan to operate it, particularly in times of accidents. The Fukushima incident was one of the cases where an unexpected event caused an accident. In these cases, I’m influenced to believe there is a potential harm, however I know there are many methods of cleaning, removing and storing escaped radionuclides before it affects population.
Twelve of the students who participated in this assessment thought that nuclear power plants are safe under certain conditions. For example, three students thought that nuclear power plants are safe given that they are restricted to safe locations. In the words of Samir: “they are safe in the stable areas, but Japan is right on multiple plate areas, bad call.”

Out of the twelve students, impact was mentioned by four of them and likelihood was mentioned by three of them, and seven of them mentioned neither impact nor likelihood. Six students mentioned that the Fukushima accident has influenced their view of the safety of nuclear power plants. Marco happened to be in China, relatively close to Japan, at the time of the accident. He wrote that the accident has influenced his opinion: “The safety of nuclear power plants is relatively OK, but through the incident, I have doubts now on the safety measures taken to ensure that nuclear power plants are not prone to damage from environmental disaster.” Clint felt that nuclear power plants were not safe but that there was no alternative: “I think that nuclear power plants are unsafe but are relatively necessary for sustainable movements as they are better than coal/fossil fuels. The incidents made me realize of the potential harms of nuclear power plants.” Luis was the only student who explicitly stated that nuclear power plants were not safe by simply stating, “Nuclear power plants aren’t reliable.”

The summary of student scores on the first part of the question and details about the second part is found in Appendix I. Comparing the first and the second question, one student who found nuclear power plants unsafe also disagreed with the statement from the first question. Out of the remaining ten who disagreed with the first question, five said that nuclear power plants were safe and five said they were safe with a qualifier.
Although it may seem that students who disagreed with the first question should find the nuclear power plants safe, it was not so for the majority of students. This could be because of the way that the first question was framed—the students were looking for the hole in the argument and when asked about safety they expanded their argument. For example, Samir, who disagreed with the first statement (“ramification are much more severe”), found nuclear power plants safe if built in safe areas (“they are safe in the stable areas, but Japan is right on multiple plate areas, bad call.”). Federico disagreed with the first statement (“depends on the scale of the accident”), but found nuclear power plants safe in general: “The Fukushima incident was one of the cases where an unexpected event caused an accident. I know there are many methods of cleaning, removing and storing escaped radionuclides before it affects population.”

**The First Nuclear Power Plant Activity**

In this section, I will describe the findings from the first nuclear activity. More specifically, I will outline the selection of the website and the subsequent estimation of empirical probability. Prior to the activity, the students were divided into six groups formed by Breanna based on classroom management decisions. The groups consisted of: 1) David, Fahad, Samir, and Sasha; 2) Blair, Robert, Federico, and Cai; 3) Luis, Jared, Luca, and Clint; 4) Adam, Andrew, Zu-Zhang, and Mario; 5) Jordan, Alex, and Aaron; 6) Nathan, Lee, Anjun, and Marco.

**Deciding On Reliability**

Three of the six groups decided that the *Guardian* website was the most reliable source, two stated that the World Nuclear Association website was the most reliable, and one group stated that it was a tie between the *Guardian*, the World Nuclear Association, and
Greenpeace. The reason for claiming that the *Guardian* was the most reliable was that the *Guardian* is not a stakeholder in the issue and therefore is deemed a trustworthy organization. The groups that identified the World Nuclear Association website as the most reliable based that on the claim that it is the organization that directly records the data. The group that claimed the *Guardian*, the World Nuclear Association, and Greenpeace as equally reliable justified their decision on the fact that all three had domain names that were either .org or .uk.

In terms of the least reliable website, four of six groups chose Greenpeace, and two groups chose the Ecoholic website. The students felt that Greenpeace was a stakeholder in the issue with a strong anti-nuclear stance and as such it should not be trusted. For example, Marco said:

> We felt that Greenpeace was the least reliable as the organization that was striving to make the general public believe that the nuclear energy was the least effective or the most devastating. So we believed that the data presented on the website was going to be exaggerated to appear that nuclear energy is very negative.

Samir and his group found the Greenpeace website to be unreliable because they considered the Greenpeace to be a stakeholder:

> We chose Guardian which had the most comprehensive list, it was the most reliable newspaper, we thought that was a pretty solid reasoning of why we use this source. So the Guardian is the most reliable because it is not the stakeholder on the issue and it’s widely available and obviously Green Peace is the least reliable.

Prompted by the statement that Greenpeace is a stakeholder in the issue, I responded: “What about the first one [the World Nuclear Association]?” Samir respond that the WNA’s site was “obviously reliable because they track nuclear incidents and I don’t think they would lie.”
Although the World Nuclear Association is an organization devoted to nuclear energy advocacy (World Nuclear Association, 2013), the group did not see it as biased. Two groups claimed that the Ecocentric blog was the least reliable, since the nature of the blog is that it is not heavily edited and it does not cite sources.

**Choosing the Website**

Although there was more variation in determining which website was most reliable, five of six groups ended up using data from the *Guardian*’s website (Appendix J). Most of the comments claimed that the reason was the *Guardian*’s presentation of the data: the accidents were given a numerical ranking in terms of severity, with the addition of a detailed description of the incidents as well as the use of colour to designate severity. Adam explained his choice of using the *Guardian* as follows:

> We decided to use Guardian because it has a depth of resources, it had more than one source, it’s pretty reliable source as well, also it helps that it classified each nuclear accident for us, it pretty much it gave us most information it could using different sources.

The following exchange between Anjun and Marco illustrates how students were using the various aspects of the data presentation—how the numerical information together with the qualitative information helped them make sense of the data:

Marco: But also if you look at Guardian.
Anjun: How many does it list?
Marco: They list a lot! [counts]….33
Anjun: 3 major ones?
Marco: 3 major ones out of 33.
Anjun: Chernobyl? Three Mile Island and Fukushima?
Anjun: Fukushima is level 5.
Marco: Chernobyl is much much worse. Chernobyl was horrific!
Estimating Empirical Probability

The second part of the activity required students to estimate the empirical probability of a nuclear power plant accident. The students were first instructed to determine the number of nuclear power plant accidents from the data source they selected in the prior exercise. After that, the students were instructed to access the euronuclear.org website to determine the total number of nuclear reactors that are in operation. The website contains the following text:

On December 20, 1951, at the Experimental Breeder Reactor EBR-I in Arco, Idaho, USA, for the first time electricity - illuminating four light bulbs - was produced by nuclear energy. EBR-I was not designed to produce electricity but to validate the breeder reactor concept. On June 26, 1954, at Obninsk, Russia, the nuclear power plant APS-1 with a net electrical output of 5 MW was connected to the power grid, the world's first nuclear power plant that generated electricity for commercial use. On August 27, 1956 the first commercial nuclear power plant, Calder Hall 1, England, with a net electrical output of 50 MW was connected to the national grid. As of January 18, 2013 in 31 countries 437 nuclear power plant units with an installed electric net capacity of about 372 GW are in operation and 68 plants with an installed capacity of 65 GW are in 15 countries under construction. As of end 2011 the total electricity production since 1951 amounts to 69,760 billion kWh. The cumulative operating experience amounted to 15,080 years by end of 2012. (European Nuclear Society, 2013)

Using the information from the website, there are different ways to estimate the probability of an accident. The worksheet suggested to students to use either the total number of nuclear reactors or the total time they have been in operation.

The method of calculating probability varied between groups. For example, Federico, Blair, Cai, and Robert calculated probability by deciding that the total number of “major” accidents was three. They then proceeded to calculate the total number of hours since nuclear energy was first introduced in the early 1950s.

The group found that the total number of days since the beginning of the utilization of nuclear energy was 18747—the students calculated the number of years since 1951 and
multiplied it by 365 to roughly get the answer. The students then divided 3 (the number of major accidents) by 18747 to obtain the answer of 0.00016, or 1 per 6249 days. They also obtained the answer as a percentage, namely 0.016%.

Adam’s group used the total number of accidents and incidents independent of severity to arrive at the number of nuclear “incidents” at 33. During the presentation, Adam explained their result in following words:

In terms of deciding what to include, we decided to go with all of them regardless of their severity as we figured that even the least severe incident has potential to be harmful and we wanted to know how many times in total has something gone wrong with nuclear power plant. That gives us a very workable number.

The students then took the number of accidents and divided it by the total number of reactors in operation to arrive at the probability of 0.07.

Three groups decided to make a judgment on the severity of the accident and use a cut-off value. David, Jared, Luca, and Clint used the cut-off value of 5 on the International Nuclear Events Scale (INES). By this measure, they calculated there were 6 nuclear accidents. To arrive at the total probability of nuclear accidents they divided 6 by 442, arriving at the probability of 0.013. They also expressed the probability as 1.3%. They were explicit neither about the units used nor about the interpretation of what the probability means.

Daniel’s group also used a cut-off value, but selected 4 instead of 5:

We included incidents on the Guardian website that were on the scale from 4 to 7 anything less than that was insignificant, so is you use that scale there are 11 incidents and then we use the number of 442 current active nuclear power plants. We divided that so there is a 2.5 % chance of nuclear power plant having an accident.

Marco’s group used the cut-off value of 5. They justified their result as follows:

We did not include every single incident into the result because there is the larger number of incidents that were small scale compared to the ones selected, small scale
in the sense that it did not have lethal effects, in comparison of the larger types of incidents that were selected that included the radioactive leak into the environment, long term health and environmental effects.

The students then divided the number of accidents (6) by the total number of years that all of the reactors were in operation (reactor years) which was given as 14286 to arrive at 0.00042. The group did not provide the unit. Alex’s group did not arrive at a numerical answer. Instead, they said that the probability was small.

**Decisions Based on Probability**

During the last part of the activity, the students were required to make a decision based on the probability estimate they had obtained. Blair’s group claimed that the probability they arrived at was small, saying that there was a “small chance per day that there would be something happening with the nuclear reactor.” Blair then expressed the answer as “3 over 18747” days. He concluded that “this means that there is 1 accident every 17 years, which is fairly safe.”

During the presentation of Adam’s group’s results, Mario stated: “Based on the probability, we think that nuclear power plants are safe, because there is low probability that future accidents will occur.” Breanna then asked whether the probability was small. Adam said that it was “basically 7%.” Adam then gave additional arguments supporting the safety of nuclear power plants in terms of the trade-offs and impact: “We also have to take into account that we as the society need energy and the trade-off is a small chance of something going wrong with the large gains in terms of energy and we thought it was a relatively small risk.” I then asked, “So, you used your own personal views?” Adam responded: “Yes, we did. Because it is a personal question. Yes, I don’t think you can… Necessarily statistics
require personal views. People like to think it’s the law of statistics, but there is always an interpretation.”

Daniel’s group decided that the probability of accident was small but did not give any other contextual information or explanation. Sam said there was a 2.5% chance of nuclear power plant having an accident. I then asked if they had decided that nuclear power plants were safe. Sam said that: “This is safe because we said so… It’s the small number.”

In summary, all six groups claimed that the probability estimates were small and that this implies that nuclear power plants are safe.

The Second Nuclear Power Plant Activity

The second activity involving the safety of nuclear power plants took place about a month after the original activity due to the structure of the course. Students were divided into the same six groups and given an activity in which they had to assess the safety of nuclear power plants using data including likelihood and impact.

I introduced the activity by telling students that this was a continuation of the first activity which had been done almost a month prior to this one. I summarized the group findings from the first activity, pointing out that every group had concluded that the probability of a nuclear power plant accident was small. After this, I told them that the next activity would use the same methods used by financial analysts and others to assess risk. The objective of the activity was to introduce students to the assessment of the impact, coordination of the likelihood and impact, and the idea that the assessment may be value-laden.

The first question on the worksheet asked what else besides impact should be considered in determining the risk of a power plant accident. I wanted students to think about
impact, however, in most cases, examples involved different factors influencing risk (for example, location of power plant accident, the age of the reactor).

In Group 4, Andrew and Adam were leading the discussion, but Andrew was writing it on the construction paper. Adam was trying to reason by himself without any feedback from other group members. For the first question, he equated safety with probability: “We have to look at safety. No…actually…safety is the same as probability.” He then distinguished between the probability and the ability to respond to accidents: “How likely for the accident to happen is not identical to how well one can be able to deal with the accident.” He concluded that the factor influencing risk is connected to the ability to respond to an accident and told Fahad to write: “safety protocols and number of people working there are the factors to analyze.”

While Jordan (Group 5) was writing the answers, Alex said, “We have to consider how many people were hurt and how bad the accident was.” In other words, he suggested that they should look at the impact of the accident. While they were having a discussion, Fahad from the other group yelled, “This is Geo!”—explaining that they had discussed the Fukushima accident in their geography class. The group also identified other factors such as demographic and socio-economic characteristics. They also echoed Adam’s group in saying that what matters is preparedness before and response after the accident. They agreed that what also matters is the structure of the country, such as social, economic, and political systems. They struggled to formulate what also mattered, so Alex finally wrote: “deep rooted sociological factors.”

Other groups concentrated on geographical and physical factors that may increase the risk of an accident. For example, Luis, Jared, Luca, and Clint wrote that the factors
influencing risk include the environment around the nuclear power plant, location, plate boundaries, the time of year, and predicted weather. The list of the factors discussed by each group can be found in Appendix K.

**Definition, Assessment, and Comparison of Impact**

In this section, I will describe the students’ definitions of impact and how they calculated it. When asked what other factors besides probability influence risk, no one explicitly mentioned impact but they mentioned other circumstances/factors that may influence both probability and impact. In terms of the measures of impact, two groups offered the International Nuclear Events Scale (students in these two groups had done a geography project that dealt with nuclear power plants). Other students listed measures of nuclear impact such as nuclear waste and the amount of radiation.

Four out of five groups disagreed with the working definition of impact in terms of fatalities as presented on the worksheet. One group agreed but they interpreted the question to ask whether the statement was a working definition of impact. For question six, none of the groups revised their numbers. For the calculation of impact, out of the five groups for which we have data, two groups used the ratio of the total deaths from the coal power plant accident to the total deaths from the nuclear power plant accident (645), one group used the ratio of the number of deaths per accident (around 1.5), and one group used deaths per accident (18.11 and 31). One group thought that the estimation offered in the activity was biased and stated that the impact of a coal power plant accident was “big” whereas the impact of a nuclear power plant accident was “astronomical.” The following episodes illustrate students’ reasoning about impact.
David, Samir, Sasha, and Fahad (Group 1) were reading question six about other ways we could determine the impact of nuclear power plants. Fahad and David said that we could also look at the environmental impact. Samir noticed that the statistics given in the table included only short-term fatalities although the nuclear power plant accident may also have long-term fatalities; Fahad agreed with him. They seemed to be puzzled by the idea that they were expected to produce a numerical answer. Fahad said, “How can I have numerical answer? How can intuition give me numerical answer?” David responded, “I was not aware that intuition was fully quantitative.” Everybody else laughed about the comment. They decided not to answer the question.

From the group discussion, we can see that the students took issue with the fact that intuition and beliefs can be a part of the calculation of probabilities.

Adam, Andrew, Zu-Zhang, and Mario (Group 4) were answering the sixth question and trying to figure out what other information can be used for calculation of impact.

Mario: We need to consider the environmental impact.
Adam: Yes, like coal CO₂ emissions are more damaging to the environment than nuclear reactions.
Adam: Andrew, can you search for “coal nuclear power environment”? Andrew enters this term into a search engine. Adam looks over his shoulder and points at the link and tells Andrew to open it.
Adam: Nuclear power compared to coal power. Right there! Click! Oh here, the third one…Coal power burns 10,000 lbs of coal a day…. Causing an added 9292 deaths per …Oh no (excitedly): 9292 deaths! Per year! There!
Adam starts reading the question 7 but Andrew is going back to the previous question asking him: Coal burns 10000 lbs of coal a day….and then...
Adam: …which causes an added 9292 deaths per day.
Andrew: That per day?
Adam: Positive [inaudible].
Andrew: No way! [as if he is surprised that the number is so large]

The above conversation shows the influence of content knowledge on the students’ risk decision. It also shows how students benefited from the Internet access to get more
information about the content. The exchange about the rate of coal-related deaths (9292 deaths per year gets misinterpreted as 9292 deaths per day) illustrates how easy it is for individuals to misinterpret information.

Andrew read the question about the comparison of the impacts of nuclear power plants to those of coal power plants and repeated out loud: “You will try to determine whether the risk of an accident is higher for coal power plants or nuclear power plants.” Alex interjected, “Nuclear power plants are probably ten times more devastating than coal.” Adam said, “We should write, nuclear power plants are more devastating.” They kept reading quietly, Adam said, “That’s what we were saying, how likely is for the event to be devastating—safety protocols again.”

Andrew was reading the question 5 out loud and was commenting about the table. Adam: We need a calculator{writes on the construction paper}:
\[
\frac{20276}{1119} = 18
\]
So to answer this, nuclear has a greater impact.
The impact is approximately 2 times greater than coal.
Because, nuclear accidents, one accident caused 31 deaths, whereas for coal, one accident caused 18 deaths. So nuclear has a greater impact.
Andrew: Yeah
Mario: Yeah, so the impact of the nuclear power plant accident is twice as big.
The students expressed the comparison of the impact of a nuclear power plant accident to the impact of a coal power plant accident in two ways: Mario said that the impact of nuclear power plant accidents was twice as big, whereas Adam’s explanation was more descriptive and was expressed in terms of ratios—but instead of saying 1 to 31, he said that 1 accident caused 31 deaths.

Luis, Jared, Luca, and Clint (Group 3) were working on filling out the table in the worksheet. They started filling out the table in the worksheet (see below) and had no problem entering the information for the probability. When they got to the part that required them to
calculate the impact of nuclear power plant accidents and coal power plant accidents, Luis was adamant that the numbers provided were not sufficient. Other members did not seem willing to argue with him. Instead of quantitative measures, Luis used qualitative descriptors, namely “big” (for coal) and “astronomical” (for nuclear). He also commented: “Japanese might consider nuclear power plants more dangerous.” Luis’ response suggested that Luis believed strongly that nuclear power plants were dangerous. He did not find quantitative information sufficient and decided instead to base it on his beliefs about the safety.

**Coordination Between Probability and Impact**

All of the groups realized that risk can be seen as the product of likelihood and impact. Four groups concluded that the impact of the coal power plant accidents was greater than nuclear and Luis’ group concluded the opposite (based on the premise, described above, that the impact of a nuclear power plant accident was “astronomical”). Out of the four groups who offered their opinion about the objectivity of the risk assessment, one group claimed that the calculation was objective, and two groups thought that they were objective (“we used mathematics”) but that their values may have skewed the answer.

Adam, Andrew, Zu-Zhang, and Mario were working on calculating risk from the data on probability and impact. Adam was leading the discussion:

Adam: OK, we put down the probability of nuclear power plant as 0.0746, which means that the probability of coal accident is 0.746. We determined the impact of nuclear was 31, so Andrew, 31x0.0746?
Andrew: 23.
Adam: This makes no sense. Do it again.
Andrew: 2.3. Why is it like this?
Adam: The impact is 31 but this only happens 0.0746 times.
Adam: Since we don’t have anything that tells us otherwise: Risk equals probability multiplied by impact
Adam: Interesting how although this one is way more damaging (nuclear) it’s way less likely to happen frequency wise.
From the above vignette, we can see that Alex was surprised that impact was small. Adam gave the explanation that although the impact is “31, it only happens 0.0746 times.”

When asked how their beliefs influenced their thinking, Adam responded: “They did not—we just used math.” His words imply that calculation was equivalent to objectivity. After a little bit of reflection, Adam also added: “But… the inherent belief in safety of nuclear power plants may have skewed our answer.”

Jordan, Alex, Aaron, and Ray (Group 5) were confused about why I wrote the probability of the coal power plant accident as “10x.” They asked me to explain my reasoning and I said, based on the probability, that was a conservative answer. They started working on the table from the worksheet. Since the probability of the nuclear power plant accident that they obtained was 0.00042, the value they calculated for the coal power plant accident was 0.0042. They had earlier concluded that the impact of the nuclear power plant accident was 1.5 times the coal accident. They decided to use the base line for the impact of the coal power plant accident of 100, which meant that the impact for the nuclear power plant accident should be 150. After that, they multiplied the corresponding values and wrote:

- Overall risk of coal: 0.42
- Overall risk of nuclear: 0.063

I asked them what they did with the numbers. Alex told me they had multiplied them, explaining that “you have to have some sort of measure and the most natural thing is to multiply them.” For the last question, they were asked if their reasoning was objective. During the group discussion, Ray had argued that their answer was not objective, but they ended up writing: “No, the calculations are objective.”

The above discussion suggests that the group found multiplication “natural” but could not give another reason why it makes sense to consider the product. They found their results
to be objective since they had quantified their answer. The summary of the groups’ findings can be found in Appendix K.

**Case Two: St. Hubertus Secondary School**

St. Hubertus Secondary School is a co-educational publicly funded religious school in a large metropolitan area in Ontario. The school is situated in an ethnically and socio-economically diverse community.

**Students**

There were 23 students in the study: 19 females and 4 males (Table 5), with an average age of 16. They were enrolled in a grade 11 enriched class, which means that the topics covered in the grade 11 Ontario curriculum were expanded. Overall, it corresponded to the IB1 standard level curriculum. The course was one semester long. The class met every day for 75 minutes from September until the end of January.

The class participated in a two-hour-and-fifteen-minute group activity on determining the empirical probability of nuclear power plant accidents. The activity was introduced with a 45-minute lecture on the definitions of terms: probability, theoretical probability, and empirical probability—demonstrated with coin flips. Following the activity, the groups presented their findings on the probability of nuclear power plant accidents, which took 75 minutes. The second group activity lasted 75 minutes and involved the safety of nuclear power plants using data including likelihood and impact. The objective of the activity was to introduce students to the assessment of the impact, coordination of the likelihood and impact, and the idea that the assessment may be value-laden.
Table 5

*The List of Student Participants at St. Hubertus Secondary School*

<table>
<thead>
<tr>
<th>Student</th>
<th>Pseudonym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 1</td>
<td>Chloe</td>
</tr>
<tr>
<td>Student 2</td>
<td>Emina</td>
</tr>
<tr>
<td>Student 3</td>
<td>Sara</td>
</tr>
<tr>
<td>Student 4</td>
<td>Hiroko</td>
</tr>
<tr>
<td>Student 5</td>
<td>Karl</td>
</tr>
<tr>
<td>Student 6</td>
<td>Larissa</td>
</tr>
<tr>
<td>Student 7</td>
<td>Maya</td>
</tr>
<tr>
<td>Student 8</td>
<td>Connie</td>
</tr>
<tr>
<td>Student 9</td>
<td>Priya</td>
</tr>
<tr>
<td>Student 10</td>
<td>Joao</td>
</tr>
<tr>
<td>Student 11</td>
<td>Andy</td>
</tr>
<tr>
<td>Student 12</td>
<td>Anoush</td>
</tr>
<tr>
<td>Student 13</td>
<td>Talia</td>
</tr>
<tr>
<td>Student 14</td>
<td>Dale</td>
</tr>
<tr>
<td>Student 15</td>
<td>Mina</td>
</tr>
<tr>
<td>Student 16</td>
<td>Natasha</td>
</tr>
<tr>
<td>Student 17</td>
<td>Amira</td>
</tr>
<tr>
<td>Student 18</td>
<td>Lina</td>
</tr>
<tr>
<td>Student 19</td>
<td>Joseph</td>
</tr>
<tr>
<td>Student 20</td>
<td>Louvie</td>
</tr>
<tr>
<td>Student 21</td>
<td>Iris</td>
</tr>
<tr>
<td>Student 22</td>
<td>Helen</td>
</tr>
<tr>
<td>Student 23</td>
<td>Pouneh</td>
</tr>
</tbody>
</table>

A majority of students did not have their own graphing display calculator (GDC) and a GDC was assigned to them at the beginning of each class. The students did not bring laptops to school and there was no wireless Internet access. There was a smartboard in class, but it was seldom used. Unlike the Dale Academy students who all had institutional email addresses, St. Hubertus Secondary students’ did not have school email accounts. Also, there was no wireless access for students in the school. Through an informal survey, I found out that the students’ only access to email was through social networking sites such as Facebook.
Teacher

Clarissa was a teacher in her early forties. She grew up in a European country and immigrated to Canada with her husband in the early 2000s. She had received a science degree in her native country, and after moving to Canada she had completed a Bachelor of Education degree. She had been teaching at St. Hubertus for five years. She was confident in her mathematical and pedagogical content knowledge; she identified probability as the most challenging area for her as a mathematics teacher and learner.

Initial Assessment

As with Dale Academy, the purpose of the initial assessment was to test whether students possessed intuitions about impact and the coordination between the likelihood and impact. The same two questions that were used for Dale Academy were used for St. Hubertus. I decided to keep the same theme (nuclear energy and the Fukushima accident) because it had been only half a year since the accident and I thought that students would have at least some knowledge about the accident.

During the initial written assessment, students were given a question concerning the safety of nuclear power plants as follows:

Do you agree or disagree with the following statement? Explain your reasoning. “There have been around 500 nuclear power plants built since the 1950s. So far there have been only three significant nuclear power plant accidents. This makes nuclear power relatively safe compared to other means of generating power.”

Twenty students participated in the assessment. Three students agreed with the statement, four partially agreed (agreed with a qualifier), eleven disagreed, one agreed implicitly, and one neither agreed nor disagreed.
Language of Impact

Out of the twenty students, eight students based their argument on impact. For example, Anoush wrote:

I disagree with this statement because nuclear power plant accidents are massive and dangerous. There have already been three. That is three too many. Of course every workplace has minor accidents; that is how we learn from our mistakes. But, when dealing with such a dangerous and life-threatening item, all precautions need to be taken.

The student uses words such as “massive,” “dangerous,” and “life-threatening” to describe the impact of nuclear power plant accidents. The student also differentiates qualitatively between different levels of impact, i.e., “minor accidents” vs. “dangerous and life-threatening.”

Out of eight students who based their argument on impact, one agreed with a qualifier, one neither agreed nor disagreed, five disagreed, and one implicitly disagreed. The words and phrases used to talk about impact included: “the effects,” causing a “great deal of damage,” “massive,” “dangerous,” and “devastating”. A summary of the results for the students who based their argument on impact is given in Appendix L.

Reasoning Not Based on Impact

The twelve remaining students did not use impact in their reasoning. Instead, they used different lines of reasoning, such as content knowledge. For example, Anoush wrote:

You cannot answer this definitely on “only 3 significant power plant accidents” alone. One must compare it to the other means of generating power and the number of “significant accidents” those means have generated. Examples could be coal-base power plants, wind, and water resources etc. But to answer the question, I disagree because I think wind and water is much safer.
Besides using information from the question, the student also takes a critical stance towards the data by questioning the meaning of “significant accidents.” In addition, the student’s previous knowledge of other sources of energy is used to answer the question.

In the subsequent class, the second question was given to students in order to test whether they would use judgments based on probability. The marking scheme was the same as for the Dale Academy students (see the methodology section). The students were awarded 1 point for each statement (with partial marks allowed):

- Earthquake (tsunami) hit Japan.
- Damaged power plant cooling system, causing meltdown.
- Many people and the environment were affected.

Twenty-two students from the St. Hubertus class answered the second question. The mean score was 1.5 with the standard deviation of 0.8. The lowest mark was 0 and the highest was 2.5. Table 6 presents the summary of the student scores and exemplars from each category.

Table 6

<table>
<thead>
<tr>
<th>Score</th>
<th>Number of Students</th>
<th>Exemplar</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>“I do not know anything”</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>“Nada, I only know that it involved a nuclear reactor in a nuclear plant.”</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>“There was an earthquake in Japan that left millions of people without homes. I do not remember anything specific about this accident.”</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>7</td>
<td>“I don’t know much about the accident. I just know that Fukushima Daichi accident was a nuclear explosion that followed the earthquake in Japan.”</td>
<td></td>
</tr>
</tbody>
</table>

76
“During an earthquake in Japan a nuclear reactor was in danger of contaminating a large area. Workers risked their lives to go in and fix what they could and limit the damage.”

“What I know I that the earthquake had caused the nuclear plants of Japan to react and was released. This has caused many problems to the environment as well as the people living in Japan. I know that this nuclear release will cause numerous health issues.”

Many students qualified their answer by stating that they did not know much, compared to Dale Academy students who did not do this at all. Thirteen students expressed uncertainty about their knowledge, with 10 students claiming that they don’t know (“I don’t know, but”) and three students expressing the uncertainty in a different way (“I think…”).

For example, Hiroko, who received the score of 2.5, wrote:

I don’t know much about what happened but I know there was an earthquake in Japan and I think that it wrecked a nuclear energy plant. It was not safe for the people in Japan so they were suffering, it damaged the environment and its surroundings.

Talia, who received a score of 1, wrote:

This is the first time I am hearing about this accident unless I forgot about it previously. Even though I know limited about this I do know however that people did get hurt and some may have been killed due to this accident. Nuclear energy plants are very dangerous to deal with and handle, because it does cause a threat to society and it does pose a problem to the government.

Twelve St. Hubertus students explicitly referred to the harm to the population of Japan caused by the accident, contrasted with only six students at Dale Academy. For example, Iris, who received a score of 1.5, refers to the harm caused to the environment: “In addition, there are concerns with the bodies of water in the Pacific Ocean. The accident resulted in infectious water which would affect the species underwater (fish, etc.).”

Connie, who received a score of 1.5, describes her emotions about the accident:
The Fukushima Daichi accident was very sad. Water and food sources were contaminated, buildings were wrecked leaving millions homeless and the economy was hit hard. What is even more sad, but honorable, are the workers at the power plant who decided to stay behind and not evacuate the highly radioactive and dangerous plant in order to stabilize it. The radioactivity would reduce their life spans significantly and threaten their lives with the risk of cancer (ex. Like Marie Curie) due to exposure. The support from the rest of the world was amazing.

The second part of the question addressed the students’ opinions about the safety of nuclear power plants. Twenty-two students participated in the assessment. Out of those students, 12 stated that nuclear power plants were not safe, six did not explicitly state whether they were safe or unsafe but expressed the need for more safety, two claimed that they were safe with a qualifier, and two did not know.

Out of 12 students, eight mentioned impact and two alluded to it. Only one mentioned likelihood. For example, Iris wrote:

In my opinion, the nuclear power plants are not safe. Indeed they provide energy; however if an accident occurs, many problems could arise. The Fukushima incident has influenced my thinking because it has erupted many problems that would affect the future generations. Therefore, I feel that nuclear power plants are not safe.

From her statement, we can surmise that the student is concerned with the impact of nuclear power plants, and especially their impact on humans (“problems that would affect the future generations”). Priya is even more categorical about the harm (impact) of the nuclear power plants. She wrote: “In my opinion, I would not even consider safety. I am completely against nuclear power. Knowing about the Fukushima incident just strengthens my reason as why I oppose the idea of nuclear power plants. It causes more harm than benefiting from it.”

Louvie evoked her personal feelings about nuclear power plants and uneasiness about the idea of living close to them when expressing her opinion:

My opinion on safety of nuclear power plants is that it is not very safe. I don’t know much about them but when I think of finding a place to live I definitely do not think of moving next to a nuclear power plant. I think that there is a higher chance of
something going wrong when dealing with nuclear energy as opposed to, let’s say, electromagnetic energy or radiant energy. Also, the consequences of nuclear energy are more detrimental than the consequences of other forms of energy.

Six students did not explicitly claim that nuclear power plants are safe or not safe, but stated that the safety needs to be enhanced. Out of these, one student mentions impact and no one mentions likelihood. For example, Maya states:

I think not enough focus is regarded towards nuclear power plants
If safety was more enhanced, the Fukushima accident would not have taken so long to contain. All that nuclear power wouldn’t have spilled out. The damages this earthquake caused will appear in the next generations
I think that there should be many precautions regarding safety issues. They should be prepared for the worse because you never know what could happen.

Out of the two students who claimed that nuclear power plants are safe with a qualifier, one of them mentions impact and none of them mention likelihood. For example, Joseph tried to mention relative safety as well as the dangers of the nuclear energy by deeming it “relatively safe and a great source of clean energy”, but acknowledging that “with it also comes the risk of a devastating meltdown which can destroy a lot of land, property and most importantly people.” The analysis of the second question is given in Appendix M.

**The First Nuclear Power Plant Activity**

In this section, I will describe the findings from the first nuclear activity. First, I will describe how students were selected following by the description selection of the website and then describe their estimation and interpretation of probability. The students were divided into five groups. The groups were formed by Clarissa based on classroom management decisions. The groups were: 1) Priya, Iris, Maya, and Joseph; 2) Lina, Andy, Louvie, Karl, and Connie; 3) Hiroko, Daniel, Anoush, Natasha, and Amira; 4) Chloe, Mina, Larissa, Dana, and Sara; 5) Helen, Talia, Pouneh, and Emina.
The students were given a worksheet in which they were presented with four websites. However, since there was no wireless Internet access in the classroom, I provided students with printouts of all the websites. As with the Dale Academy students, the websites were:

- World Nuclear Association – an organization representing the interests of the nuclear energy industry
- Greenpeace – an environmental activist group, giving a comprehensive list of incidents and accidents
- Datablog – the statistics blog from the Guardian
- Ecocentric blog – the environmental blog from Time magazine

Unlike the activity that took place at Dale Academy, I decided to explicitly state on the worksheet that the World Nuclear Association represented the interests of the nuclear energy industry.

**Deciding on Reliability**

Four groups stated that the Guardian was the most reliable website. One group (Chloe’s) stated that Greenpeace had the most reliable data. The reason why the Guardian was seen as the most reliable was that the students found it to be the least biased and most impartial. Priya’s group was the only group that went further than simply stating that the Guardian is reputable; they found out what the source was (the UN nuclear watchdog) and questioned the reliability of it, but concluded that they still trust the Guardian most because, as Priya stated:

> The Guardian created the website and they do not have the statement supporting either side of the issue, they are impartial. So they are on the fence, they did not say that nuclear power plants are bad and they did not say they were good, they are basically just stating facts.
In terms of the least reliable sources, students unanimously chose the World Nuclear Association website. For example, Lina’s group said that “their perspective is very narrow and only focused on the nuclear power.”

Choosing the Website

All of the groups selected the Guardian as the data source. The students listed the presentation of data as the reason for choosing the Guardian: the Guardian lists all of the major accidents in an organized manner, uses summaries, and is clear and comprehensive. Priya’s group justified their choice in the following way:

The way they define an accident is like a map. They start from the highest level to the lowest explaining the degree of the accidents, the effects it has on people and the environment. They also map out the nuclear accidents. We used the INES because it states the nuclear levels. We can use these levels to explain the other list on the degree of the accident.

The student choices of data source are summarized in Appendix N.

Estimating Empirical Probability

The activity required students to estimate the empirical probability of a nuclear power plant accident. Similar to the Dale Academy students, the St. Hubertus students were instructed to determine the number of the nuclear power plant accidents from the data source they decided to pick in the prior exercise. After that, students were instructed to access the euronuclear.org website to determine the total number of nuclear reactors in operation (see the Dale Academy section).

Using the information from the website, there are different ways to estimate the probability of an accident. The worksheet provided suggestions to students to either use the total number of nuclear reactors, or the total time they have been in operation. I also
instructed students to make sure to write the unit, since the Dale Academy students’ arguments about probability were weakened by the fact that they did not describe the units.

The ways of estimating probability varied between the groups. Priya, Iris, Maya, and Joseph (Group 1) decided to calculate the number of accidents per total reactor years. They made the following calculation:

\[ \frac{\text{accidents}}{\text{years}} = \frac{33}{1400} = 2.3 \]

Although the calculation was correct, the students made an incorrect interpretation claiming that the probability is 2.3% for 1400 years, instead of saying that per one reactor year there are 0.0023 accidents, or 2.3 accidents per 100 reactor years. As we can see in the next section, this interpretation influenced students’ decision on safety.

Group 2 and Group 4 calculated probability by calculating the number of years since the first reactor, and then dividing the total number of accidents by the number of years. For example, Lina’s group argued that since the Guardian lists 33 incidents,

\[ \frac{33 \text{ incidents}}{59 \text{ years since first recorded incident}} = 0.55 \text{ average incidents per yr since 1952} \]

They concluded that there has been about 1 incident every 2 years.

Three groups took the total number of accidents that they found from the Guardian’s website (33), and divided that by the total number of nuclear reactors currently in operation to arrive at the value of 0.08 accidents per nuclear reactor. Most of the groups explicitly stated the unit except for Group 5.

**Decisions Based on Probability**

During the last part of the activity, the students were required to decide on the safety of nuclear power plants based on their calculations. When asked if the value obtained was big
or small, Group 1 said that the value was small, offering additional information, written on the construction paper: “Small. 2.3% for every 1400 is small. This is likely saying 1.15% for 500 years.” However, when asked whether this means that nuclear power plant are safe, on the back of the construction paper they wrote in large letters: “NO!” (Figure 3). The marker permeates both sides of the paper and the “NO!” is in stark contrast in terms of size to the rest of the writing.

Figure 3. The group writes a big “NO!” over the construction paper.

During the presentation, when prompted to explain why they did not consider nuclear power plants safe despite a very small probability of something going wrong, Joseph and Priya responded:

Joseph: The thing is, if it does happen, to cause an accident, repercussions of that accident… they are severe.
Priya: Even though the accidents are very limited…
Joseph: It’s not worth the risk.
Priya: Yeah, they are not worth the risk.

Group 2 wrote that the probability is large because “any number above 0 is too big. The safety of even one individual’s life should not be compromised.” When asked if they are
safe, they wrote: “No because even if there was only one incident it would still be risking other people’s lives. 10 windmills that produce electricity that would fall is safer than 1 nuclear reactor explosion.”

Daniel’s group responded that the probability of 0.076 is close to 10% which means that the probability is large. When asked about the safety, they performed additional calculations:

\[
\frac{33}{432} = 0.076388888\% / 60 \text{ years}
\]

Therefore the \( P(\text{nuclear accidents per year}) = 0.0013\% \)

the probability of a nuclear accident per year is very low

When asked if this means they are safe, Daniel responds:

By the numbers they are safe, but one accident can change everything

Chloe’s group wrote that the probability was large because it should not happen at all.

In terms of the question of whether the nuclear power plants are safe or not, they wrote, “Yes and no.” When asked what this meant, Mina said: “They are safe because it is very unlikely for something to go wrong, but when it does, they are completely unsafe!

Group 5 found that the probability was small and that this is considered safe, but when they answered the next question, they wrote: “It is safe, according to the Guardian info but we still think it is not safe→ #s too small. It’s a possibility though still rare. There’s too much at risk.”

**The Second Nuclear Power Plant Activity**

I introduced the activity as a continuation of the previous day’s activity. On this day, quite a few students were absent, so the groups were altered. There were four groups in total: 1) Priya, Iris, Maya, and Joseph; 2) Connie, Daniel, Karl, Andy, Lina, and Louvie; 3) Hiroko, Chloe, Dana, Mina, and Larissa; 4) Helen, Pouneh, Amira, and Talia. The data source for all four groups is identical and consists of group video, presentation video, construction paper
The learning objective of the activity was to introduce students to the assessment of impact, coordination of the likelihood and impact, and the idea that the assessment may be value-laden. The questions were written in such a way that they elicit student thinking about impact and coordination between likelihood and impact.

The first question on the worksheet asked what else besides impact should be considered in determining the risk of the power plant accident. I wanted students to think about impact, however, in most cases, examples involved different factors influencing risk (for example, location of power plant accident, the age of the reactor).

Based on their knowledge of the safety of nuclear power plants, the students in Connie’s group identified various factors influencing risk. Some of these factors can influence probability, some impact, and some both. Students disagreed on whether some factors were relevant, as the following conversation implies. Namely, in conversation with Louvie, Connie said that the type of nuclear power plant may matter. Louvie said either way it would be the same considerations. Connie then agreed. From the discussion, we can see that the students conclude that the type of radioactive material is not a factor in the risk of a nuclear power plant accident. However, a couple of minutes later, Connie reiterated that the type of the material did matter:

Connie: I think some power plants are more dangerous than other power plants based on the material they have.
Joao: Yeah, it should.

This time, Joao agreed with Connie that the type of material did matter. The conversation also shows that students sometimes reformulated their answer and what was said made more sense to their peers ("some power plants are more dangerous than other power plants based
on the material they have” is more descriptive and clear than the statement “different types of radioactive material”).

Louvie and Connie agreed right away that the location of nuclear power plants is a factor (“if they are located in ‘natural disaster prone areas’”). The group also agreed that human factors influenced the risk of a nuclear power plant accident:

Connie: How skilled the people…are?
Louvie [enthusiastically]: Yeah! That’s true!
Joao: Yeah, mostly education…
Louvie [Starts writing down and saying out loud while she writes]: How capable the workers are…
Joao: Like if you are in a third world country…obviously the technology…technology may be good enough…but obviously it won’t be as good as technology like from…
Connie: Canada!
Joao: Canada or the US or the country that is developed and it has like universities or anything else like that.
Karl: Japan!
Joao: Japan…Shut up!

Based on my knowledge of the individuals in the group, Joao made the last comment because Karl’s family comes from Japan and Joao thought that Karl was boasting of the fact that Japan is considered developed. The episode illustrates how individuals’ beliefs and stereotypes about a certain group or a phenomenon also can influence their beliefs about risk.

Pouneh (Group 4) suggested safety as the factor influencing risk. Helen considered this answer as trivial since she considered safe to be a situation in which there was no risk,: “How would the safety of the nuclear power plant impact an accident? If it’s safe, then it will be no accident.” She was laughing while talking as if she found Pouneh’s statement too obvious. Pouneh replied that they could question the safety of the power plant with which Helen agreed. Further into the discussion, Pouneh suggested that “the type of accident” is another factor determining risk:
Pouneh: Wait, the type of the accident.
Pouneh: Put in bracket serious.
Helen writes serious.
Amira: And then “not serious.”
Pouneh [laughing]: What’s the word for “not serious”?
Amira [laughing]: Not serious?!
Pouneh: I don’t know!
Amira: Unserious! I don’t know!
Helen [writes]: serious to “safe” accidents

The idea of a “safe accident” may seem paradoxical, but from the context of the question we can see that “safe” is used as an antonym of “serious.” In this case safety does not refer to zero risk; instead, safety means “low impact.” The list of the factors influenced by each group can be found in Appendix O.

**Definition, Assessment, and Comparison of Impact**

In this section, I will describe the students’ views on defining impact as well as on calculating it. Group 2 was at first struggling with this question and ended up asking me for help. Instead of answering, I asked them what data could be used for impact. Connie answered, “How many people are hurt; death rate.” I asked if there was anything else that could be used besides this. I then posed a question: “If I told you that there was an accident, what kind of questions would you ask?” I did this in order to make the concept of impact more concrete.

Joao: Environmental.
Karl: A barren wasteland.
Connie: What happened, environmental consequences.
Joao: The amount of people…
Connie: How many people hurt but not injured.
Joao: The amount of people that worked there…Never mind.
Connie: How about injured but not dead?
Joao: The economic tolls of the accident
Connie: I was thinking, like the aftermath, you can get…How about how long it takes them to recover?
Louvie: Yeah.
Connie: How much money they need?
Karl: Financial damage.
Joao: Remember how in the information we looked at they had...
Connie [interrupts]: What was that…economic consequences
Connie: How much it needs…How much after it was damaged...
Karl: The cost of repair.
Connie: Yeah.
Joao: Yeah the surrounding area…If there is an accident, people cannot go to work, people can’t…all that stuff.
Louvie: OK, how many people were hurt, economic consequences.

By prompting the group to think of the aftermath of an accident, the students were able to come up with different ways of defining and describing impact. The conversation seems to flow well. Some of the answers suggest that students were trying to visualize the impact (“a barren landscape”; “if there’s an accident, people cannot go to work, people can’t… all that stuff”). Students started with concrete examples and then tried to generalize them (“how much money they need?”; “environmental damage”)

Connie (Group 2) was looking at the second table that had fatalities added to the number of accidents. She was surprised by the number of fatalities for coal. The focus then shifted to explaining the difference between the nuclear power plant accident and the coal power plant accident. She was surprised that the coal power plant accident caused more fatalities:

Connie [reading]: “with more than 5 immediate fatalities…” What a hell, it’s more for coal?! “Do you agree with this working definition, why or why not?”
Louvie: I think it should be three or more…OK…If one or two people die it could be their own mistake, they could have done something.

As suggested by the comments above, Louvie believed that the smaller number of fatalities can be attributed to human error rather than the features of nuclear power plants and the nature of nuclear accidents. Louvie explained the discrepancy by drawing the distinction between intermediate deaths and the long-term effects:
I think I would disagree because a lot of people could die from a nuclear accident but afterwards. This says immediate death. For example, five people could die from immediate deaths from coal or whatever, but those could be the only five people whereas nuclear energy impacts more. So five people may not die right away but slowly more people will die from it, and more people will die as the result, because the impact is bigger.

Joao and Connie agreed:

Joao: Coal is not as much of a…
Connie: Yeah! Is not as big.
Joao: Coal, when you get into an accident, the accident is more of a physical thing, nuclear, it’s a…like it lasts longer
Connie: Yeah it last longer.
Connie: Babies in Hiroshima start coming out like deformed.
Joao: Yeah! Like, Chernobyl, remember, that happened long time ago and people can’t still live there.
Connie: Yeah!
Joao: And they say that the land won’t be fertile for another, like…
Connie: …million years.
Joao: Yeah.
Karl: Centuries.
Joao: I think it’s lower than million, but whatever.
[they are laughing]
Joao: The answer is more like thousands

In the episode, the students were surprised by the numbers, however, after the element of surprise had passed, they were able to justify that the immediate impact for coal was higher but the long-term impact was still greater for nuclear, drawing on their knowledge of nuclear accidents. In the discussion during the group presentations, Connie summarized their view of immediate versus long-term impact as follows:

I was thinking also because it says “immediate impact”, so, like, let’s say, a coal power plant accident, if someone died, if 5 people died first and they could have been the only people that died. Just because it’s immediate, it was like recorded, but for the nuclear power plant, there could have been more long term effects. So five people may have not died first, but, like, millions of people could have died afterwards, and that went uncounted because of the working definition.

While attempting to provide the working definition of impact, Helen (Group 4) seemed to distinguish between “safety” and “impact”: 
Nenad: There are more accidents, right? But, there are more coal accidents, but the impact is smaller. If you just looked at the number of deaths.
Pouneh: So what would it be worse, like, having a nuclear accident or having a coal accident?
Helen: Nuclear!
Nenad: Well, just looking at the number of people died, it looks like it’s nuclear.
Helen: But what’s safer, guys?
Nenad: It looks like it’s nuclear, but the number of people died is not the only way to measure impact.
Helen: So we just have to focus on making nuclear power plants safe. But I am still against them!

Faced with the table that contains information on both the number of accidents as well as fatalities, Connie’s group was calculating the impact by dividing accidents per fatality, rather than the more conventional way of representing impact which would be the number of fatalities per accident. For example, the impact for coal is 1/31 accidents per fatality, which equals 0.032. Joao, who did the calculations, then obtained the percentage which is 3.2, meaning the accidents per hundred fatalities (but he did not explain the significance of percentage). For the coal power plants, the students obtained the result of 0.0552 accidents per fatality, which equals to 5.5%.

The students then concluded that coal had a greater impact since 5.5 is greater than 3, whereas in reality it is the opposite. At the time, I believed that this was a good introduction to the reciprocal relationship between accidents per fatality versus fatalities per accident.

After their calculations, I came to talk to them to make sense of their result.

Nenad: OK, how did you figure out the risk, the impact here?
Connie: I think Joao divided incidence by fatalities, right?
Joao: Yeah, and I got percentage for each.
Connie: And you also did 1/31, right?
Joao: Yeah.
Nenad: Oh, so you did 1/31 and 1000 divided by that? And you compared the numbers?
Joao: Yeah.
Nenad: OK, that another way of doing this, which number was bigger?
Connie: Coal?
Joao: I think coal was bigger. I can’t remember. It’s somewhere on the sheet.
Nenad: Yeah…one thousand…yeah this is another way of doing this. Nobody has done it this way but this is a perfectly valid way of doing it.
Connie: Nice job, Joao!
Joao: It said to compare them so I just got percentages of each.
Connie: OK, so 5.5….
Nenad: But this is just a…OK so the first number was 5.5, right? So, accidents versus fatalities?
Joao: Yeah, fatalities, it was five immediate, right?
Nenad: Yeah.
Nenad [writes, on the sheet]: OK, so this is the ratio of accidents over how many people died. Right?
Joao: Yeah.
Nenad [pauses]: …OK, so the first one you got…I just need the decimal, 0.05, right?
Connie: Yeah.
Nenad: And the other one, the accident over fatalities was 0.03?
Connie: Yeah.

For me, the challenge was to describe that, although 0.03 was smaller than 0.05, the impact for nuclear is bigger. Instead, I resorted to telling them that, although their way of calculating is correct, the easier way would be to take the reciprocal of the numbers.

Connie: So you do it the other way?
Nenad: Yeah, so if 20276 people died divided by 1119, that means there were 18 people killed on average for each accident for coal.
Connie: OK.
Nenad: There were this many accidents, but 18 people died on average.
Connie: What about for nuclear?
Nenad: 31 people died.
Connie: 31 people died.
Nenad: Per accident.
Connie: So which one has higher impact?
Nenad: You could do this and then this way, but if you want the other way, the accidents divided by fatalities, you want this number to be hmmm, as…The smaller the number, the more fatalities, it would be opposite, but what makes more sense to people is to go the other way around. Yes, 31, 18 (point on the sheet). So which one has higher impact?
Nenad: By how much, how many more times? If this is 18 and this is 31?
Connie: Divided by...
Joao: Divided, no 31!
Nenad: 31/18. Right?
Connie: That’s 1.7.
Nenad: 1.72. 1.72 more times.
Nenad: You could totally present it like that, that’s interesting.
Connie and Ann Marie: Yay! [laughing]
Joao: So, we were right.
Connie: No.
Louvie: We were right.

Students then proceeded to express the impact in the way I taught them. Later, during their presentation, students explained both ways of expressing impact:

Connie: Our question 5 had a correction. We will present both methods. Actually, what Joao did [laughs] is divide accidents by fatalities so he got that the impact is 5.5% greater in terms for accident per fatalities for coal and for nuclear was 3.2%.
If you go down here [points at the construction paper], we divided fatalities per accident which is what people are more accustomed to, for coal you get 18 fatalities per accident but for nuclear you get 31 fatalities per accident. And for the percentage, it was 1.72 times greater than coal...
Nenad: I just want to say...that you guys... for the second table... most people... one way to do it is 20000 divided by 1100, and you get 18 and then you get 31. But what that group, what your group did, was to go the other way around, so they took 1100 and divided it by 20000, so they got smaller numbers. So that’s another way of looking at this. But, what makes more sense if you are going to present this to the media, and to people who do not know that much math, it’s better to say: oh, it’s 31 fatalities per accident for nuclear and 18 for the other one.
So, yeah, that’s good.

Based on the above discussion, my explanation was not sufficient and I consider this as a lost opportunity of talking more about reciprocal quantities and the meaning of \( \frac{1}{31} \) versus \( \frac{31}{1} \).

Hiroko (Group 3) defined impact as any difference before and after the event, which is a very comprehensive definition of impact.

Hiroko: What was it? Impact is anything that makes slightest difference.
Chloe: Everything that makes difference to surrounding area. No, everything that makes difference.
Hiroko: Anything that makes a difference.

The students in Group 4 were not able to answer the second question so they asked me for assistance. I explained the significance of impact. Pouneh then suggested: “Oh!
Wouldn’t it affect money because the governments pass it on?” I agreed with the statement, and Helen then wrote: “financial impact.”

The group agreed that their answer to the first question could serve as the basis from which they could derive the impact of the accident. The group also agreed that they did not have concrete data available, but Amira suggested that they could use that “thing that happened in Japan.” Helen then asked how they could “fuse this information [from the first question] to determine the impact of an accident.” While posing this question, Helen placed her hands over the information written on the construction paper as if physically scooping all of the information and trying to turn it into impact (Figure 4).

The examples show an importance of gestures in reasoning about risk—the gesture in this case represents the synthesis of all of the information into the assessment of impact.

![Figure 4. Helen wants to know how to take this information and find the data that will help determine impact (the hands are blurry because of the movement).](image)

They called on me to check on the work they were doing. I reiterated that they could look at financial cost and environmental cost. When I left, they were trying to make sense of what I had said:
Helen: What else? Is that it?
Pouneh: He said environmental, financial. And government. [on the recording, I never mention the government]
Helen: What? Like how? I don’t understand that?
Pouneh: OK. When something happened, they go kabooie.
Helen: Yeah?
Pouneh: And there is a lot of stuff to fix.
Amira: It’s going to take money to clean it up, it’s going to take money to fix.
Helen: It’s asking what data we can use to determine the impact of an accident, that’s like finding the probability of an accident. What kind of data can we use?
Amira: Financial cost.

In this case, students visualize the scope of the impact by creating a scenario of the situation.

Group 4 was trying to define the impact of a nuclear accident on the society.

Pouneh: It should be financial, environment, and government in brackets.
Helen: Oh yeah! [writing] Environment, what else?
Talia: Government? Who cares about the government? [laughs]
Amira [laughing]: Who cares about the government?
Pouneh: Put government, too.
Helen: Why does a government need to recover? People need to recover.
Pouneh: Because environment and government are different.
Talia: But government has responsibility for the environment.
Pouneh: Exactly!
Helen: Government does not need to recover.
Pouneh: Yeah, they do! They need to fix a problem.
Helen: Yeah, but that would be something different.
Amira: It has to be done by the people who own the plant.
Talia: But if there is pollution doesn’t it have to be addressed by the government?
Helen: People can go against the government.
Pouneh [resolutely]: If the lives are being lost the government is involved!
Helen: Yeah, but how does that relate to the question?
Pouneh [loudly]: I don’t know! He said something about the government that’s all I remember.
Helen: No! If someone…ok…some [inaudible] people would be going against him. It would be…what is it called…when [inaudible] strikes again?
Amira: Protests!
Helen: Yeah. So, it could be social impact [taps first section where it says social impacts; places the arrow next to it and writes social]
Pouneh: Social uprising.
Helen: What do you mean by the government, though? I don’t understand that.

In the above example, students are trying to define impact, but in order to do so, they are trying to make sense of the structure of the society. Based on their discussion, the model
of the society they suggest can be represented by Figure 5, which can also be viewed as a mathematical object. The model of the society is important, because it lets students figure out the structure of the impact that an accident can have on the society. Notice how students started talking about impact and then tried to work out how different parts are connected. Also, notice how students view environment, people, and government as separate but interacting with each other.

![Diagram of Government, Environment, People]

Figure 5. Representation of the group’s model of the society. Arrows represent the direction of influence.

The following vignette from Group 4 illustrates the importance of values in determination of risk. The students read the working definition of impact as the number of accidents with fatalities greater than five. They spent a significant amount of time arguing whether the working definition was valid. A great part of the discussion was about whether it is right to ignore any deaths.

Helen: You guys, do you agree with this definition of impact? “Number of accidents resulting in five or more immediate fatalities.”
Pouneh: Where?
[Helen points at it]
Amira: It says more than five.
Helen: No!
Pouneh: I don’t agree. If one person dies, they are not gonna care?
Helen: Exactly!
Pouneh: Everybody counts!
Amira: If you take this and multiply it by 5? I think that’s what you have to.
Helen [writes with the black marker]: “Risk Assessment”

Helen agreed that ignoring the accidents with a number of deaths less than five may be problematic from an ethical point of view but insisted that it still valid:

Helen: I think, maybe that is a good definition—because, what is it called?—I am not being MEAN to the people who died, that are under four, but, like...
Amira: But, any death is considered something!
Helen: Yeah, but...

The fact that the students found ignoring death problematic was confirmed by the fact that Talia and Amira would consider ignoring injuries but drew the line at death:

Talia: But if this was an injury
Amira: Yeah if it was injury!
Talia: If this was an injury it would be a different thing, but it’s death! People are dead!
Helen: So, what do I write?
Pouneh: That’s OK. It’s fine. Good enough
Helen: No. [writes] “No we don’t agree; even one death…”

Helen stopped writing and started passionately arguing that the considerations of impact should be on a larger scale and that less than five deaths is a relatively small number:

Helen: Because the impact is defined in a bigger way.
Helen: I find this weird…because the impact [tapping the question with the marker]...
Impact is a bigger thing here. We are looking at the definition of impact. Who…cares about…

Helen reiterated that one death was not important to her but also realized that this was contingent on whether she knows the person or not:

Helen: One death… who cares? No offense! If one of my friends died…
I would care if one person died from the nuclear…If I knew them. But honestly, if it’s one person, it would not really affect anyone except for the one…
Christine: I say, everybody counts!
[raising her voice] What if you are that one person that’s gonna die?
Helen: Who cares! [laughs, they all laugh] Listen! Listen to me. An impact! One person dying off in the world is not a big deal. OK, guys?
Amira: That’s true…
Christine: I understand that! But it still means…
Helen[banging her hands against the table in frustration; raising her voice]: It does not matter if it means or anything, the working definition. [gestures at the handout] What’s an impact on the world?
Pouneh: Look how stern she is.
Pouneh: I would hit you Helen. [laughing]
Talia: This can’t be the whole issue.

Helen then said that individuals’ choice of voluntarily being exposed to risk diminished the importance of their deaths: “The thing is, people agree to work in the nuclear power plants? Don’t they?” The students then called on me to ask me for my opinion:

Helen: What is your opinion? [they laugh] Do you agree with this definition (“the number of accidents…”)?
Nenad: So what do you guys think? Is this, like, it just looks at 5 immediate fatalities. Right?
Amira: So that means that it could have been later on deaths, they could have gotten injured and still between [inaudible] and also it’s the number of accidents that five people died.
Nenad: Yeah.
Amira: So, let’s say that there was one, or that there were four people that died.
Nenad: Yeah, so that’s a good thing. Maybe, they should have just included all the accidents in which people immediately died.
Helen: Yeah but I want to have impact. I want to find impact [gestures]. ‘Cause…
Nenad: Yeah, you are not happy with this definition of impact? Just looking at people died? Is that what you mean?
Helen: No. I am saying that I kind of agree with it, but they think that all deaths matter, I am not trying to be like ‘mean’ or anything [gesturing quotation marks with her hands] but it’s just how it impacts the world.
Nenad: Can we just…
[they are talking at the same time, Pouneh explains to me what Helen “is trying to say”]
Nenad: Oh, OK. It sounds cruel, but maybe, maybe it’s right. But, you have raised a good point still.
Helen: Yeah, but, sir, since….
Pouneh: So, what if it was you who is dying? [laughs]
Nenad: Then it would be extremely important for the world. [everybody laughs]
Pouneh [laughing]: Exactly!
Nenad: Especially my world.
Connie: Exactly sir!
Helen: I guess I am overruled.
Pouneh: Imagine the world without me!
Nenad: Amira, what do you think?
Amira: Personally, I don’t agree with this, if they included…if it was just deaths.
Pouneh: If a person got hurt. Right? And a family like notices that the government is not doing anything about this problem they are going to start protesting.
Amira: Yeah, but, I understand where Helen is coming from also. It’s not going to [inaudible] if one person got hurt, if one person died.
Pouneh: We all die. What is it called? Everyone…
Helen: What is the death rate in one hour?
Pouneh: Yeah, but…
Amira: I don’t think that for the argument, it should not be immediate deaths. It should be “deaths”. Because, you could got injured and die.
Talia: We can write both things.
Helen: No, I’ll just explain mine in the presentation.
Pouneh: But we have different opinions.
Helen: I’ll explain this when we present it. [looking at the next question]
Helen: Oh look how much people died!
Pouneh: See! There you go! [pauses] Now, do you care? About the people that are dying?

The lively discussion amongst the group members shows the importance of personal values on determination of risk and impact. It also shows the role of empathy in determining impact. The above argument also transformed into an ethical argument rather than a technical matter on calculating impact. As such, it is hard to argue that there is a right answer.

With my help, the group then went on to calculate that the impact of a nuclear power plant accident is 1.72 times higher than the impact of a coal accident.

Pouneh: What’s the ratio? 1 divided by 18? What’s the ratio for number 6? Nuclear has the greater impact, impact is 1.72.
Amira: 1 to 31. The ratio is 1 to 31 and 1 to 18.
Helen: What? What’s the ratio?
Amira: 1 to 31 for nuclear and 1 to 18.
Helen: 1 divided by 31.
Pouneh: It’s 31 divided by 18.
Helen [raising her voice]: No!
Pouneh [raising her voice]: Helen, it’s 31 divided by 18!
Helen: No! I am talking about the impact of coal…
Pouneh [interrupts]: 31 divided by 18!
Helen: …compared to the nuclear power plant, what is the ratio of coal to nuclear power plant, not…
Amira: OK, what about writing down?
Helen: OK, give me the pencil, so the impact of coal...
Pouneh: Are we going to use 31 divided by 18? I point something?
Helen [writes on the handout and shows it to the rest of the group]: That’s the ratio, right? Of coal to power plants?
Pouneh: Geez Louise!
Helen: ’Cause coal, power plant [points on the handout]. It’s the ratio!

Helen wrote on the handout, before she transferred it onto the construction paper.

Helen: Hold on, no wait. They are talking about impact. [reading] How does the impact…It doesn’t talk about what coal is…
Amira: the impact of coal is 1 accident, 18 deaths and it is 1 to 31 for nuclear.

On the construction paper, Helen wrote:

\[
\frac{1}{18} = \frac{1}{31}
\]

The episode suggests that students do not consider the statement that “the impact of the nuclear accident is 1.72 higher than coal” to be equivalent to “The ratio is 1 to 31 and 1 to 18”, which it is. They also do not notice that three ratios are equivalent: 31 to 18 is equivalent to \( \frac{119}{20276} \) which is equivalent to 1/31: 1/18.

From the use of a different representation of the same rational number (1.72), I conclude that these representations served different purposes. For example, 1.72 shows how much greater one magnitude is in comparison to the other and the second one contains information about how many fatalities per accident each accident causes. They may refer to the same value, but their sense is different.

**Coordination Between Likelihood and Impact**

In this section, I describe the ways the students were trying to coordinate the information between probability and impact and how, through the activity, I was trying to
shift student reasoning to the mathematical coordination using graphs and the product formula.

Group 2 students created the table listing the probability and impact for the nuclear power plant accidents as well as for the coal power plant accidents on the construction paper. They used one of the charts I provided them to plot the probability versus impact for both types of accidents. The group did not seem to coordinate likelihood and impact or to see risk as comprising of both. They seemed to understand what both concepts mean separately, but were struggling with combining them. For example, Joao said: “What the risk of it being a large impact is.” Louvie was dictating to Connie: “We combine the impact and the nuclear is greater and we know that the probability is greater? I don’t know what it says… I don’t understand.”

The students then tried to define probability (as “likeliness”) and impact as an average impact per accident, but agreed that they did not have to have a quantitative answer:

Joao: By probability we can determine how likely it is to happen.
Connie: OK! [writing] When we combine probability…
Louvie: ...we can see overall likeliness.
Joao: Yeah we can see the overall likeliness of each accident happening.
Joao: Do we actually have to combine the number?
Connie: No we are not!
Connie and Louvie: And how big the impact would be…
Joao: Yeah, how great the average impact of that accident would be.

On the construction paper, Chloe’s group wrote: “when we combine the probability + impact we can determine the overall likeliness of an accident occurring + how great the average impact will be for the accident.”

From the above statement, we can see that the students do not have a way of combining the two notions. Risk consists of two different variables that may be correlated, but the risk is not a function of two. As a side note, there is not enough evidence to suggest
that the students thought that risk was the sum of probability and impact; although they used
the plus sign, the students often use the plus sign to denote conjunction (“and”) rather than
addition.

In order to answer the final question, namely how the risk of a nuclear power plant
accident compares to the risk of a coal power plant accident, the students talked about the
long-term impact.

Karl: Basically it is long term risks… Like, basically how does nuclear power plant
accident compare to coal.
Joao: There are more coal accidents.
Ann Marie: The accidents are long term.
Connie: …detrimental.
Ann Marie: That’s completely not what I just said! See there more high risk accidents
in nuclear power plant than coal.
Connie: They are more long term and detrimental.
Ann Marie: No, Connie!
Connie: They are more damaging.
Ann Maya: No, there are more high risk accidents.
Connie: That’s what it means, they are more damaging!
Ann Maya: No, coal…
Joao: Stop using big words and start saying one is more damaging… and one is…
Who you trying to impress? This is not an English class, this is math class.
Ann Maya: Listen! No! The coal may have more accidents, but nuclear ones have
more high risk accidents!
Karl: Long term impact!
Ann Maya: That’s what I wanted to say!
Joao: Nuclear power plant, the accidents are more…
Connie: Higher fatality rate?
Ann Maya: No! More high risk accidents.

From the last part of the discussion, students seem to equate long-term impact with high risk.

It seems that the students are not seeing risk as the coordination between likelihood and
impact; instead, they are thinking of risk solely as impact.

The students then plotted the data for coal and nuclear on the chart. During the
presentation, Connie explained the chart as follows:
Connie: The next one is we had to do the chart and coal was, the impact of risk was high, but the probability of occurrence was low [points at the chart]. No the probability of occurrence for coal was high, but the risk was low and for the nuclear the occurrence was low but the risk was high [traces her finger from the upper left corner, to the lower right]. So we concluded that the higher the risk, the less likely is to happen.

Nenad: Well, in this case.

Catherine: Yes, in this case.

Nenad: In this case, the bigger the impact, we can say it’s less likely to happen.

Joao: Yeah!

From the above discussion, one can deduce that the students looked at the Impact/Probability chart in terms of the relationship between the two variables (which is what they are accustomed to). Based on the position of the two points, the students concluded that the correlation between probability and impact was negative: “the higher the risk [impact], the less likely is to happen.”

Although Group 3 calculated that the impact of the coal power plant was 654 times greater than nuclear, the group was unsatisfied with the numerical answer—they thought that the answer based on the data provided was inadequate. When it was time for the group to chart their answer, instead of relying on the numerical answers they gave qualitative answers:

Nenad: Graph, let’s try to find the risk of nuclear power plant accident? What is the probability of the nuclear power plant accident?

Hiroko: Low?

Nenad: Hmmm…Which one did you guys get yesterday?

Chloe: Yesterday we got 0.076, like 0.1 [pointing at the graph], so this is 1, and this is 0.1, and you are here. Right?

Chloe: Yeah.

Nenad: So, it’s low probability and let’s just say that…What’s the impact of the coal, really low or really high?

Chloe: Kinda in the middle.

Nenad: So, let’s call this one. So, this is coal, so see how I am just estimating this. So of this is one…How many times is then nuclear more…what’s the impact…

Chloe: Impact wise it would be over here…

Nenad: So we said it was 1.72 times more, so it’s like here
From the above discussion, we can see that, at times, I was trying to force a numerical answer, whereas the students were more comfortable with a qualitative answer which was described in visual terms: “kinda in the middle”; “impact wise it would be over here”.

Consistent with their answers and the lack of confidence in numbers, students drew the probability and impact table but left it empty (Figure 6).

\[ \begin{array}{c|c|c}
\text{Coal} & \text{Probability} & \text{Impact} \\
10 \times \text{(nuclear)} = & & \\
\text{Nuclear} & & \\
\end{array} \]

*Figure 6.* Students did not calculate probability or impact.

Similarly, the probability/impact chart did not contain numerical labels (Figure 7).

In order to make sense of the data, I decided to use the risk management approach and introduce students to contingency planning.
Figure 7. Probability vs. Impact graph for Group 3.

Group 3’s lack of reliance on the numerical data was apparent in the group presentation when Chloe said that the impact of the coal was 654 times higher but then presented the chart that showed that the impact of the nuclear power plant accident was higher. In other words, the calculations were just a mechanical operation for the group without any significance in their decision making.

Chloe: So what we have here? We have low probability, high impact. They call this medium level, so let’s see what this means. It says here…Can you find which one this is? We need high impact and low probability.
Priya: I think it’s like.
Nenad: Yeah, it’s this one. It says that risks in the bottom right corner are high importance and low probability but they are very unlikely to happen. OK. For these, however, you should do what you can do to reduce impact and you should have contingency plans.
Nenad: Do you know what contingency planning is?
Chloe and Priya: No
Nenad: If something happens…
Chloe: You have plans…
Nenad: For example, probability of a fire in this school is low but if it happens there is contingency plan, they practice how to get you out of this building, that’s the contingency plan. So the thing is, they call this medium risk, so the question is, do we have a good contingency plan for the nuclear power plant accident.
Hiroko and Chloe: No.
Nenad: For example, for Fukushima, is there a good plan if something explodes…
Hiroko: No.
Chloe: They flooded it with sea water.
Nenad: Yeah, so there was a contingency plan.
Chloe: So there was an impromptu thing, well it made sure that it wasn’t going to do anything…
Nenad: I am not trying to confuse you here…So what I am saying here is that one way to graph them is to combine them on the chart.

Again, students’ content knowledge pertaining to Fukushima was crucial.

Pouneh’s group used numerical information to plot the points on the chart. I came and helped them with labelling the axes and plotting the values (Figure 8).

Nenad: What did you get for impact? 1.7? Right? And what’s the probability for nuclear accident? That you guys got yesterday? Do you remember? 0.076?
Pouneh: Yeah.
Nenad: So, let’s take a look at this [shows the probability vs. impact chart]. What’s the probability of a nuclear power plant accident? Low. If this is 1, where is 0.07? It’s like here. If this is one [points at the top of the y axis]...
Helen and Pouneh: Oh.
Nenad [taps at the increments of 0.1]: What’s the…What about the impact? Let’s call this in the middle the impact of coal, right, it’s medium. If something happens. If this is 1, how many times is it higher for nuclear?
Helen: 1.7.
Pouneh: Almost 2.
Amira: Sir, I don’t get…
Nenad: Let’s coal this 1. Right? If this is coal, where’s the nuclear going to be?
Pouneh [points at the x axis]
Nenad: 1.72. Right? So over here?
Helen: But coal is what? Nuclear is 1.72? So this is coal, pointing at the lower area of the square.
Nenad: No, coal is like. This is a scale for the impact.
Helen: OK, so this is low impact (0 impact) and this is high impact. I am saying that coal is somewhere in the middle, let’s call it 1, and how many times is nuclear bigger? 1.72 times bigger. OK, so the probability is low. Right? But the impact is high [draws the position of it on axes]. This is where nuclear is.
The main problem with the above explanation was that the number 1 was arbitrarily placed in the middle. This had to do with the intuitive notion that a coal accident, although sometimes very devastating, does not have the global impact which a nuclear power plant accident may have.

Priya: Our probability was different than Connie’s group because our probability was 0.024 and it says to multiply to 10 to get the coal’s so it’s 0.2 and the impact of that is 1. And nuclear power is 0.02 and the impact of that was the same calculation as theirs which was 1.72. When we used the probability graphing, we got the same answer as the other group did but we also found that what we could do is multiplying the probability times impact, so what we got is this: for coal was 0.2 times 1 which is 0.2 but when you have nuclear it’s 0.02 times 1.72 which equals a lesser number than coal so when we did calculations for the table what we are basically saying is that coal has a higher impact risk than nuclear, that’s why I was confused because I thought that nuclear would have more risk impact than coal.

Nenad: So, one thing that people suggested in math when they talk about risk is to multiply the two numbers together. You have the probability and you have the impact. So, what can you do with two numbers? Well, it’s math, you might as well… you can multiply it.

But, sometimes this works but in this case, it doesn’t really show you the whole picture. So, it’s actually better to… it’s easier to use the chart and try to find it where it is.

Priya [reading]: How does the risk of nuclear power plant accident compare to coal? We got two different results, but using graph makes more sense than multiplying it.
The student answers based on the factors impacting risk, assessment of impact, and coordination between probability and impact are given in Appendix O.

**Final Assessment**

In addition to the presentations, I asked the students the same question as on the initial assessment (Appendix C) in order to additionally document their reasoning and beliefs about nuclear power plant safety following the activity. The final assessment’s findings for each student are presented in Appendix P. It shows that only Natasha stated that nuclear power plants were safe compared to the coal power plants, while Karl said as much in an implicit way. Everyone else believed nuclear power plants were not safe. Comparison of the initial and final assessment results indicates that most of the students referred to impact on the final assessment. For example, on the initial assessment, Iris wrote:

I do not agree with the following (sic) statement because alongside with the invention of nuclear power plants, there has also been the invention of generating power using wind (windmill) and water (Niagara Falls). These types of power generations could be considered safer than nuclear power plants because they deal with natural resources, which means that humans do not have a daily direct contact with these generators. Therefore, there would be less accidents with these types of power generators, which would be considered to be safer than power plants.

The student uses her previous knowledge to offer alternatives to the use of nuclear power plants. On the final assessment, however, Iris made a clear distinction between likelihood and impact:

\[
\text{Probability}= 0.6\
\]

I disagree with the statement. Although not a lot of accidents occurred, the impact of one accident is extremely dangerous. It affects people who live in the area as well as the following generations. Thus 0.6% may not seem to be big; however the impact of the accident is big.

Compared to the answer from the initial assessment, the student makes specific reference to the impact.
Natasha disagreed with the statement on her initial assessment: “the consequences of nuclear power plant backlashes are far-reaching and very potent.” On the final assessment, the student gave the following answer that makes reference to both likelihood and impact:

From the group work, the probability of the risk of a nuclear power plant per year was very low. A nuclear accident would happen less often but with more far reaching effects. Other plants using different resources to generate energy i.e. coal has more accidents/year than nuclear power plants. Our contingency plans are also very meagre (sic), but without large-power generating plants to replace nuclear power, nuclear power is relatively safe compared to other means of generating power.

Comparing the answers from the initial and the final assessment, we can see that the student used impact in two different ways. In the initial assessment, Natasha used the idea of impact to argue that nuclear power plants are unsafe, whereas in the final assessment, based on the results of the activity, she argued that nuclear power plants are safe, despite the fact that they are low-probability and high-impact events. This is the only example of a student whose belief about the safety of nuclear power plants in the beginning and at the end of the study was different.

Connie used the information from the activities to answer the question as follows:

No, I do not agree with this statement. For one, the word “significant” is very subjective depending on this sources bias. Secondly, any man operated activity should have a fatality rate of 0- anything higher and it is unacceptable. However, this is not a perfect world; disregarding plant accidents, there are many other issues associated with nuclear power- spillage while being transported as the main example. Spilling these harmful chemicals can seriously damage the environment and affect others around the area. Any incident with people being harmed should be counted as a “significant nuclear power plant incident” but it is not. The likes of Chernobyl and Fukushima (but also bombing of Hiroshima) left a great immediate impact but even greater long term consequences. There have been many coal accidents but an average of 18 people die per accident while 31 people died (instantly, this is not counting those being crippled to the risk of cancer etc.) in one accident. So, in conclusion, I do not think they are safe 😞

Talia mentioned the safety of effects as well as whether all accidents get recorded:
I do not agree with this statement because it is very rare to have not even 1 percent out of 500 nuclear power plants only 3 significant nuclear power plant accidents occurred. Nuclear power plants have a very big impact but a less chance of occurring. Even though the probability of them actually happening is very low the effects are not safe, they are really dangerous. Just because only 3 significant power plant accidents occurred does not mean that others that happened did not get recorded or weren’t significant enough to be noticed.

Mina also quoted the information from the activity, though incorrectly:

I disagree with the statement. A significant accident means that 10+ people died directly from the accident therefore there were only 3 incidents where 10+ people died directly. This leaves out the number of times when less than 10 people died directly or when people were injured. And when a plant has an accident the effects are severe and widespread.
Chapter Five: Discussion

In this chapter, I will answer the research question that was posed in the introduction. The answer to the question “How do secondary school students reason and make decisions about risk?” is divided into subsections on assessment of probability, assessment of impact with critical elements, coordination between likelihood and impact, the role of context and content knowledge, and the role of feelings and beliefs.

The second question is: “What pedagogical practices and curricular components are needed for supporting students’ understanding of risk?” The pedagogical practices section is divided into the consideration of the inclusion of traditionally “non-mathematical” content knowledge into the mathematics classroom, the importance of the availability of resources, and the inclusion of multiple representations of risk. The question of curriculum components is illustrated with the expectations from the Ontario Curriculum grades 9 through 12.

Research Question: How Do Secondary School Students Reason and Make Decisions About Risk?

The findings suggest that the source of data (the four websites) was chosen based on reliability and the visual presentation of data. The judgment about reliability was based on reputation, sense of disinterestedness, neutrality, caution towards Internet documents, and trust in authority. In both settings, students found the Guardian website most trustworthy, being a “reputable newspaper.” For many students, a source was reliable if it was seen to be disinterested and neutral. Specifically, for the Dale Academy students, the Guardian was considered the website that was not a “stakeholder in the issue” (David, Fahad, Samir, and Sasha) whereas the Greenpeace site was deemed unreliable because it had a clear agenda which was seen as anti-nuclear. Interestingly, the World Nuclear Association (WNA), a pro-
nuclear power advocate, was not seen as a stakeholder, possibly because the students were not aware of its agenda since they were never explicitly given any information about it. On the other hand, the students at St. Hubertus were given brief descriptions of the sources and the WNA entry specifically stated that WNA was sponsored by the nuclear industry. The students unanimously found WNA to be unreliable. For example, Chloe, Mina, Larissa, Dana, and Sara found that WNA has “political and financial motives.” This is consistent with Kolsto’s (2001) study in which the power company was found to be unreliable because it had a financial interest in the issue.

The Dale Academy students were given four choices for the data source—two blogs (the Ecocentric blog associated with *Time* magazine and the *Guardian*-associated blog), the Greenpeace website, and the World Nuclear Association website. Interestingly, the students did not classify the *Guardian*’s website as a blog, while *Time* magazine’s website was categorized as a blog—possibly because it has the word “blog” in the title. Some groups dismissed the Ecocentric blog because the blog format was seen as unreliable—Adam, Andrew, Zu-Zhang, and Mario stated that blogs are generally not edited and proofread for content. More bluntly, David, Jared, Luca, and Clint did not trust websites that were not .org or .uk. These concerns about online content are also echoed in the Levinson et al. (2012) study in which two groups were questioning the reliability of information online. For example, a math teacher (Ella) finds a source questionable because it could be from “any old website…could be one person” (p. 221). The students in my study, however, seemed to have a heuristic which they used to differentiate between online sources (e.g., blogs are not reliable) rather than being sceptical towards all information found online.
Levinson et al. (2012) found that students “recognize the role of trust and authority in giving meaning to the data” (p. 224). Consistent with this, two groups in my study found the World Nuclear Association (WNA) most reliable because they are the authority on the issue and they are involved in the production of information: Blair, Federico, Robert, and Cai stated that WNA was “an organization measuring those things”; Jordan, Alex, and Aaron echoed this sentiment by saying that WNA was “the source that records the actual data.” This trust in people (authoritative bodies) that are involved in direct observation and measurement is consistent with the findings in Levinson et al. (2012), in which they reported that a participant (Linda) finds the spine doctor’s recommendation reliable because he “knows more about it than the other people, and he’s seen more of these people” (p. 224).

Gal (2004a, 2004b) lists the questions of validity of data—arguments and data that support claims made within the data source—as an important component of the critical question which assist in the critical evaluation of data and the claims made about the data. As mentioned above, there is a solid body of evidence that the students considered reliability but there is virtually no evidence that the students questioned claims made within the specific data source (the four websites). This is consistent with Kolsto’s (2006) finding that pupils evaluated sources of knowledge more than they evaluated the content of the statement.

However, the students did consider the presentation of data within the document. Many students (e.g., Adam from Dale Academy) claimed that they chose the Guardian’s website because of the data presentation: the accidents were given a numerical ranking in terms of severity with the addition of the detailed description of the incidents as well as the use of colour to designate severity.
Determining and Interpreting Probability

Probability Estimates

Determination of probability was presented to the students as the calculation of empirical probability. The estimation depended on the group’s decision on the data source from the previous step. Findings showed that students used various ways of calculating empirical probability. However, even the groups who used the same data source (e.g., Guardian) differed on the data that was included in the calculation. For example, David, Jared, Luca, and Clint used the cut-off value of 5 on the INES scale, bringing the number of nuclear accidents to 6, whereas Daniel’s group also used a cut-off value, but 4 instead of 5. These values depended on the students’ evaluation and judgment about the “severity” of accidents.

This can be explained by the Levison’s et al. (2012) pedagogic model of risk since the estimation of probability was influenced by the students’ beliefs on what constitutes a serious accident. However, it also shows that the decisions about impact (interpretation of INES scale) are not separate from the decisions about probability, suggesting that the estimation of probability is also dependent on the estimation of impact, which is not explicitly stated in the Levinson et al. pedagogical model.

Representation of Probability

In the Levinson et al. (2012) study, the teachers’ representation of probability (fractions versus natural frequencies) depended on the context. The findings in my study confirm the context-dependency of representations. Some of the groups in my study moved between different representations as they were making sense of the data, and also to defend their claims. For example, Federico, Blair, Cai, and Robert calculated that the probability of a
nuclear accident was 0.00016 accidents per day, but they also represented the answer as 3 accidents in 18747 days, or alternatively 1 accident in 6249 days. However, later, when the groups were asked whether this accident showed that nuclear power plants were safe, they said they were. They supported their claim by saying that there was one accident in 17, yet again changing the representation—in this case the representation was used to make the number more approachable, as the interval of 6248 days may not be as tangible as 17 years. This shows that the interpretation of the estimate of risk as being small (on the far right of the Levinson et al. model, Figure 2) has influenced the representation. This is something that seems not to be explicit in the Levinson et al. model, since in the Levinson et al. model the representation of probability influences the estimation of probability, whereas the converse statement is neither documented nor discussed.

Lina, Louvie, Connie, Karl, and Andy also went from the decimal representation (0.55) to one involving frequencies, saying that there is 1 accident every 2 years. The preference for natural numbers has been widely documented by Zhu and Gigerenzer (2006), whose research shows that individuals’ probabilistic reasoning is improved if natural frequencies are used instead of probabilistic estimates (fractions and decimals).

Some of the groups in both schools showed elements of being on the highest level of Watson and Callingham’s (2003) construct (critical reasoning about rate). However, some students showed a lack of understanding about rational numbers, for instance, incorrect use of percentages amongst one of the St. Hubertus groups. Both groups also made mechanical mistakes in the calculation and communication of the results; there was no mechanism for checking the work amongst the groups.
There was also a lack of contextual understanding of rates. For example, in both cases, there were instances of students calculating the ratio of accidents per nuclear reactor by using the current number of reactors and the total number of accidents (since the 1950s), whereas the more consistent way would be to use the total number of reactors, past and present. Only one group used the notion of reactor years (days) which is the most common way to express operation of nuclear power plants amongst the experts in the field of risk assessment.

**Interpretation and Decision Making Based on Probability**

Once the students produced the value for the probability (the probability estimate), they were asked whether this indicated that the probability was small, and then, consequently, they were asked to decide on the safety of nuclear power plants. The findings showed that all of the Dale Academy students found the numbers to be small, whereas at St. Hubertus three groups found the numbers to be large and three found them to be small. Interestingly enough, Adam, Andrew, Zu-Zhang, and Mario found 0.076 accidents per reactor to be a small number, whereas Chloe, Mina, Larissa, Dan, and Sara found the same value to be large, arguing that 7.6 accidents per 100 reactors is not acceptable. When asked about the value, Adam said that they also took their personal views into consideration. This confirms Pratt and Levinson’s claim that the interpretation depends on students’ beliefs and also supports the Levinson et al. (2012) pedagogical model.

The relative frequencies students used for estimating probability had units (accidents/year). (My instruction at Dale Academy did not specifically suggest that students use units, whereas St. Hubertus students were instructed to use them.) The use of units may have given additional context and meaning to the probabilities.
Determining and Interpreting Impact

Qualitative Representation of Impact

There is evidence that students possess pre-existing informal (intuitive) knowledge of impact. From the pedagogic view, this is very encouraging because, in many other domains (such as assessment of probability), there is strong evidence that individuals’ intuitions are often erroneous (see, for example, Kahneman, Slovic, & Tversky, 1982). As it was seen from the study, this informal knowledge has a potential to be used in the instruction. The initial assessment in both classrooms shows that students use different language to talk about impact (e.g., “massive” and “dangerous”). Other words used to express impact include: “big,” “astronomical,” and the students even used the phrase “a barren landscape” to visualize the impact of the Chernobyl accident. This corresponds to what Pratt et al. (2011) label as “fuzzy qualitative descriptors,” which students in his study used for the purpose of a rough quantification of impact (“serious,” “massive,” “bad,” “fine,” “big”) (p. 339).

This is also consistent with the Levinson et al. (2012) study in which the teachers used phrases such as “impact on her life,” “pain threshold,” and “prohibitively dangerous option” to describe impact. The authors state that there was no opportunity for teachers to quantify impact. They also suggest that a meaningful quantification of impact and probability can only be done in an inquiry-based approach where the students can apply their values, representations, and experiences. This is the reason why the students in my study were given the impact statistic, and why I operationalized impact in terms of accidents and fatalities.

Reasoning based on the magnitude of impact leads to reasoning about rational numbers—proportions, rates, and reciprocal values—confirming Watson’s thesis that proportional thinking should be in the foreground of research about data. The findings
showed that the students were making use of equivalent fractions, rates, and percentages. Sometimes they were correct (Blair’s group, described above) but sometimes the use of rational numbers was incorrect. For example, some students were incorrectly using percentages.

Some students did not recognize that the statements were equivalent: 1.72 was the same as 31/18 which is the same as saying that the ratio was 1/18 to 1/31. However, it could be that the students thought that those statements, although mathematically equivalent, conveyed different contextual information. This stresses the differences between mathematical reasoning and quantitative reasoning in context (Mayes, Peterson, & Bonilla, 2012). The study as presented presents the case for the quantitative reasoning in context.

Another quantitative concept that the students were having difficulties with was the concept of reciprocal values. For example, St. Hubertus students understood that 31 fatalities/accident was a greater risk than 18 fatalities/accident. However, they did not understand that 1/31 accidents/fatality was the greater risk than 1/18 accidents/fatality.

Mathematical instruction underplays the importance of units. In the quantitative reasoning in context, however, the units are very important. My study shows that units were seldom used by Dale Academy students, while they were more often used by St. Hubertus students, which may be a consequence of them having been explicitly instructed to use units.

**Coordination Between Likelihood and Impact**

Unlike the studies of Levinson et al. (2012) and Pratt et al. (2011), the students in my study attempted to quantify both probability and impact. However, once quantified, there was a question of what to do with obtained numerical values. The students used various techniques to coordinate probability and impact—Dale students were instructed to multiply
the two numbers, whereas the students at St. Hubertus used the graphing method (as suggested by Pratt et al.). Reflection on the Dale Academy students’ use of the utility model (multiplication formula) confirms the observation made by Pratt et al. (2011) that, by reducing decision making to the product formula may have compromised the complexity, rendering the “decision-making process … irrelevant and meaningless” (p. 442). The Dale students’ result of the product formula simply confirmed their overwhelming consensus that nuclear power is safe compared to other means of producing energy. The one group that disagreed decided not to use numerical information at all; instead, it used the qualitative descriptor of the impact of nuclear power plant accident as “astronomical.”

The St. Hubertus students’ use of the graphing method enabled them to visualize the relationship between likelihood and impact, and gave them more diverse ways of coordination. This is consistent with Pratt’s call for the offering of other methods of quantification (p. 442). Mathematically speaking, the graphing method can be made equivalent to the product since the area of the rectangle defined by the point and the axes equals the product of the likelihood and impact.

However, in terms of the QRC framework, the graphing gives students an opportunity to locate the risk and then make risk management decisions about how to interpret it. For example, the area of the rectangle corresponding to nuclear power plant accidents—small probability, large impact—can be interpreted as medium risk; however, the students can consider contingency planning in terms of the accident. The graphing method does not necessarily make students make more objective decisions (the St. Hubertus students were still in line with their previous beliefs), however, it preserves the complexity by giving them
the opportunity to use the language of risk. Also, it enables students to draw on ethical and other value-laden resources.

Some students did use the quantitative information to locate likelihood and impact on the axes, whereas some students used qualitative information. Another group also used the graph as an opportunity to ask the question about correlation between likelihood and impact—a group hypothesized that the larger the impact the smaller the probability, again leaving room for the richer interpretation.

Another characteristic of the interplay between likelihood and impact is that it does not happen only in the “final stages.” The students considered likelihood and impact at various stages. For example, some Dale Academy students considered impact when determining the probability of a nuclear power accident by considering the cut-off value. Similarly, when asked whether 7% probability was large or small, Adam stated that it is small based on impact because the negative impact is smaller than the benefits.

**The Role of Context and the Content Knowledge**

**The Role of Context**

Pratt et al. (2011) discuss whether context may impede students’ understanding of risk, drawing on examples from previous studies in which it was shown that context may be detrimental to mathematical understanding. The authors conclude that the understanding of risk is closer to statistics than to mathematics and that the context is crucial. If we strip away context and reduce the task to the mathematical coordination between likelihood and impact, we can see that the meaning is lost. The numbers have to be viewed in context.
The Role of Content Knowledge

Levinson et al. (2012) state that “there were many opportunities in the microworld for the teachers…to make use of relevant scientific knowledge in helping to evaluate risk, but none chose to do so, reflecting other accounts, where scientific knowledge and information are either marginal or irrelevant to lay decision making” (p. 228). In my study, I found otherwise—the students’ content knowledge interacted with their knowledge of risk, each at times elucidating the other. The students did seize the opportunity to use content knowledge, as the students seemed to understand that determination of risk and its various components depended on the context. For example, the knowledge about impact depended on students’ being able to recall the information about nuclear power plants. However, not only did the content knowledge influence the knowledge about risk—the converse was also true. For example, in order to determine the impact of the nuclear power plant accident, the students at St. Hubertus drew on their knowledge of the content; however, as they were trying to understand impact, they were also making sense of the society.

How the question was formed was also an important part of the context in which students reasoned about risk. If the question had been framed differently, that would have influenced the study. The way I posed the question was whether nuclear power plants were safe relative to other energy sources. Also, the students understood the question to be whether “we” should have nuclear power plants. Some students made personal connections while others did not. This is consistent with the Pratt et al. (2011) study in which the students said that they would react differently depending on whether they were making decisions about somebody else or about themselves.
The Role of Feelings, Beliefs, and Values

The affective factor is very important in individuals’ risk based reasoning. Slovic (2010) talks about the dread factor that creates mental images about the hazards of interest (e.g., nuclear power plant accident). We can infer the feeling of dread in some imagery expressed by the St. Hubertus students, for example, a student talking about the impact of nuclear power plants as “a barren landscape.” Similarly, Gregory et al. (2012) have shown that beliefs and values have to be an integral part of risk assessment and that the choice of data and the presentation of data depend on values. This can be seen in my study when Christine’s group encountered the table of fatalities and argued about whether it was valid to only consider the accidents that resulted in five immediate fatalities. One of the students had a stern belief that “every death should count,” and the other one was more pragmatic. Finally, the student drew on her personal experience, saying that it would matter to her if she was the person or if she knew the person. The students did not draw as much on personal experience as did the students in the Pratt et al. (2011) study. The reason is that the question was framed in terms of the logical statements: Are nuclear power plants safe? This can be compared to the decision statement: Should we have nuclear power plants, or more specifically, should we build more power plants in a certain area? Students did draw on their personal experiences, however. Particularly, one of the Dale Academy students was in the region (Hong Kong) when the Fukushima accident happened and he drew on this experience when making a decision about the safety of nuclear energy. In addition, another student at St. Hubertus stated that she would not like to live next to the nuclear power plant. However, because of how the question was construed, the students did not draw too much on personal experiences. Some students did show empathy (praying for Japan).
The pattern in both case studies was that the students did not seem to shift their beliefs about nuclear power plants (except in Natasha’s case). There were instances in which the exposition of quantitative data did cause students to question their beliefs. For example, some students were very surprised to find out that the fatalities for coal power plants were higher than those for nuclear plants. This is consistent with Kolsto’s (2006) claim that students should be confronted with diverse information and viewpoints. However, students tended to include auxiliary information in order to “salvage” their beliefs.

**Implications for Teaching**

In this section, I describe the implication of the study for pedagogical practices include teaching and practices that, based on the research presented in this thesis, foster students’ understanding of risk. They include integration of other subject matter, availability of resources, and multiple representations of risk as a mathematical concept. For the curricular components, I will take the exemplar of the Ontario Curriculum grades 9 through 12 and illustrate how various aspects of risk could be taught at different grades and in different courses.

**Pedagogical Practices**

The exploration of context and content knowledge in the discussion took most of the available time, compared to the mathematical calculations. This opens the practical question of how this can be done in the mathematics classroom when the pressure is often to focus on the transmission of mathematical content knowledge. The concepts of inquiry-based thinking as well as quantitative reasoning in context (Mayes, Peterson, & Bonilla, 2012) are based on the premise that quantitative thinking cannot be devoid of context. This is why students
should be encouraged to explore content that may not seem mathematical. The connection to other subjects is also consistent with the Ontario mathematics curriculum:

Other disciplines are a ready source of effective contexts for the study of mathematics. Rich problem-solving situations can be drawn from closely related disciplines, such as computer science, business, recreation, tourism, biology, physics, or technology, as well as from subjects historically thought of as distant from mathematics, such as geography or art. It is important that these links between disciplines be carefully explored, analyzed, and discussed to emphasize for students the pervasiveness of mathematical knowledge and mathematical thinking in all subject areas.

The International Baccalaureate program emphasizes the importance of inquiry-based learning approaches in its lower-level program (mathematical studies):

Because of the nature of mathematical studies, teachers may find that traditional methods of teaching are inappropriate and that less formal, shared learning techniques can be more stimulating and rewarding for students. Lessons that use an inquiry-based approach, starting with practical investigations where possible, followed by analysis of results, leading to the understanding of a mathematical principle and its formulation into mathematical language, are often most successful in engaging the interest of students. Furthermore, this type of approach is likely to assist students in their understanding of mathematics by providing a meaningful context and by leading them to understand more fully how to structure their work for the project. (International Baccalaureate Organization, 2013)

Although not stated explicitly, students in the standard level are expected to “apply the mathematical knowledge they have acquired to solve realistic problems set in an appropriate context” (International Baccalaureate Organization, 2013).

Relying on many disciplines and many sources of knowledge requires that the sources of knowledge be easily accessible to students. This is why it was important for students to have Internet access, the value of which can be seen in the way that Adam and Andrew searched for the comparison of fatalities due to nuclear power versus those due to coal power. St. Hubertus students did not have direct Internet access (only through my computer), so this may have limited their ability to argue certain points. For example, we might wonder
how the discussion on the impact of nuclear power plants on the society would have developed if Pouneh, Helen, Talia, and Amira had Internet access in order to get a better idea about the financial cost of nuclear power plant accidents such as Fukushima. This recommendation is consistent with Kolsto’s (2001) view that the students should have an “easy access to an appropriate range of information and viewpoints” (p. 1711).

**Curricular Components**

In this section, based on the findings, I explore how risk can be taught across the Ontario mathematics curriculum. I have limited my investigation to the connections that stem directly from the findings, e.g., applications of empirical probability, calculations of rates of accident, and impact. Given the applicability of mathematics, one could come up with a scenario involving risk for each expectation (for example, in the advanced functions course, proposing a function representing impact over time and finding the rate of change of the impact over time).

**Grade 9: Academic Course (Principles of Mathematics)**

In the number sense and algebra strand of the Ontario curriculum, the specific expectations relevant to the understanding of risk are: “simplify numerical expressions involving integers and rational numbers, with and without the use of technology; solve problems requiring the manipulation of expressions arising from applications of percent, ratio, rate, and proportion” (Ontario Ministry of Education, 2005, p. 30). The problems analogous to the estimation of number of accidents per reactor years would be suitable for meeting these expectations, as well as the comparison of the impacts of various accidents.

**Grade 9: Applied Course (Foundations of Mathematics)**

The number sense and algebra strand contain the following expectations:
Solve problems involving ratios, rates, and directly proportional relationships in various contexts (e.g., currency conversions, scale drawings, measurement), using a variety of methods (e.g., using algebraic reasoning, equivalent ratios, a constant of proportionality; using dynamic geometry software to construct and measure scale drawings); solve problems requiring the expression of percents, fractions, and decimals in their equivalent forms; simplify numerical expressions involving integers and rational numbers, with and without the use of technology. (Ontario Ministry of Education, 2005, p. 39)

Similar to the grade 9 academic course, the students could be given risk-related scenarios in which rates of an accident and impact could be calculated. In order to visualize rational numbers, the students could create scale diagrams of impact (e.g., comparing impact of two events).

**Grade 11: Functions (University Preparation); Grade 11: Functions and Applications (University/College Preparation); Grade 12: Advanced Functions; Grade 12: Mathematics for College Technology**

In the exponential functions section of all of these curricula, the students are expected to:

identify exponential functions, including those that arise from real-world applications involving growth and decay (e.g., radioactive decay, population growth, cooling rates, pressure in a leaking tire), given various representations (i.e., tables of values, graphs, equations), and explain any restrictions that the context places on the domain and range (e.g., ambient temperature limits the range for a cooling curve). (Ontario Ministry of Education, 2007, p. 49)

Findings showed that some students mentioned the concept of radioactivity and attempted to give quantitative predictions on how long radiation would impact the environment. For example, Joao and Connie were not sure if the contaminated land would be fertile for a thousand or a million years. In order to equip students with a way to quantify impact in terms of radiation, teachers could situate risk around the concept of exponential decay.
**Grade 11: Foundations for College Mathematics**

In the financial mathematics strand, the students are expected to “gather and interpret information about investment alternatives (e.g., stocks, mutual funds, real estate, GICs, savings accounts), and compare the alternatives by considering the risk and the rate of return” (Ontario Ministry of Education, 2005, p. 72). Here, students could be introduced to the formal mathematical definition of risk as the expected utility. In addition, the students could be introduced to the idea that decision making about risk depends on personal dispositions, beliefs, and values.

In the data management strand, the students are expected to: “identify examples of the use of probability in the media and various ways in which probability is represented (e.g., as a fraction, as a percent, as a decimal in the range 0 to 1)”; “compare, through investigation, the theoretical probability of an event with the experimental probability, and explain why they might differ”; “interpret information involving the use of probability and statistics in the media, and make connections between probability and statistics (e.g., statistics can be used to generate probabilities)” (Ontario Ministry of Education, 2007, p. 75).

The above expectations could be met by introducing the students to the concept of risk as probability and showing how the probability can be estimated. The students could also use different representations of probability. Finally, the students could be made aware of the insufficiency of the definition of risk simply as probability. Since the students are encouraged to explore the media’s use of probability, the critical elements of risk pedagogy could also be introduced.

**Grade 11: Mathematics for Work and Everyday Life**

In the savings, investing, and borrowing section of the curriculum, students are expected to: gather, interpret, and compare information about the various savings
alternatives commonly available from financial institutions (e.g., savings and chequing accounts, term investments), the related costs (e.g., cost of cheques, monthly statement fees, early withdrawal penalties), and possible ways of reducing the costs (e.g., maintaining a minimum balance in a savings account; paying a monthly flat fee for a package of services). (Ontario Ministry of Education, 2007, p. 81)

This is an opportunity for the students to be introduced to the idea of risk in finance and to the idea that risk assessment varies depending on individuals’ beliefs, values, and experiences.

**Grade 12: Mathematics of Data Management**

This is one class where the complete inquiry-based learning of risk as described in this thesis could take place. The expectations allow thorough investigation of risk as probability, impact, and coordination of probability and impact. In addition, there is room for the investigation of critical elements of the pedagogy of risk.

**Summary of Major Findings**

The study investigated how risk can be taught in the mathematics classroom. The major findings can be summarized as follows:

1. Students’ beliefs and values play a crucial role in reasoning about risk. The students in both schools were presented with authentic data. Based on the data, students were given a task to determine whether nuclear power was safer than coal. Only one student (Natasha) explicitly changed her mind about the safety of nuclear power plants. Other students held to their original beliefs. This does not mean that the data did not influence their thinking—they were often confronted with data that contradicted their claims and beliefs (e.g., when Connie was surprised that fatalities from coal power plant accidents were higher than for nuclear). In those cases, however, they would augment their arguments (e.g., by saying that fatalities for nuclear may be long-term).
2. Students’ content knowledge and quantitative knowledge influenced each other. The students were often using their knowledge of power generation, environment, and geography to strengthen their arguments about risk. The converse was also true. In their reasoning about risk, they were also making sense of the content knowledge (e.g., Connie and Louvie trying to make sense of the structure of the society).

3. The reasoning about rational numbers is fundamental for reasoning about risk. In many instances, students used proportional reasoning (e.g., determining that 0.55 accidents per year roughly translates to 1 accident per year), reciprocal reasoning (e.g., comparing 1/31 to 31/1), ratios (e.g., making sense of 1/31:1/18), percentages (converting small decimal numbers into percentages), rates (comparing fatalities per accident to accident per fatalities). Although the knowledge of rational numbers is taught in lower grades, there was still room for improvement for both technical skills as well as critical reasoning about rational numbers (e.g., the difference between using accident per reactor and accident per reactor year). The students also needed to move between different representations at various stages of arguments (e.g., Blair’s group determining that the rate of accident is 3 in 18747 days and then, during the presentation, saying that this is equivalent to 1 accident every 17 years).

4. The quantitative aspects of reasoning about risk cannot be taught in isolation from other aspects including content knowledge, beliefs, and values. The fact that calculations that students were performing tended to “confirm” their beliefs shows that their risk-based reasoning is based on more than the quantitative reasoning. If we do not explicitly teach students about the importance of their beliefs, the students are in danger of confusing quantitative reasoning with objectivity (e.g., a group’s assertion that they were objective
because they were using math). In addition, the students’ reasoning about risk evolved while they were thinking about the specific content.

5. I propose the extension of the Levinson et al. (2012) pedagogic model of risk. The findings confirm Levinson et al. (2012) and suggest that risk-based reasoning can be broken into five components: 1) knowledge, beliefs, and values; 2) representations; 3) judgment about probability; 4) judgment about impact; and 5) estimation of risk. The reasoning does not happen in any particular order. For example, the students can make the judgment about probability (e.g., 3 in 18747 as being small) and then later change the representation (e.g., 1 accident every 17 years).

Implications for Further Research

Some of the existing research suggests gender, race, and socio-economic differences play a role in perceived risk (Finucane et al., 2010), suggesting that white males tend to downplay risks compared to non-white males, white females, and non-white females. Although there is evidence that there are differences in the estimation of risk between the two classes, I am reluctant to make any conclusions based on gender, race, or socio-economic status because not enough data was collected about students’ individual histories, identities, and beliefs about the world. There is a potential, however, to conduct research that would explore the interplay between different aspects of students’ identity, beliefs, and understanding of risk in the classroom setting.

There also seemed to be gender differences in rhetorical style. Thirteen St. Hubertus students (more than half) expressed uncertainty of their knowledge about the accident (using phrases such as “I think” or “I don’t know”), whereas none of the Dale Academy students did so. The expression of uncertainty did not necessarily match with the lack of knowledge. For
example, Hiroko, who received the score of 2.5, prefaced her account of the events with, “I don’t know much about what happened, but…” St. Hubertus students also expressed their emotions in their description, whereas only one student at Dale Academy did so—the student who had been in Hong Kong had been worried about the accident.

The question of the risk of nuclear power plants was framed in terms of a judgment about safety. Another way to frame the question would be in terms of the risk decision, such as whether there should be nuclear power plants. More specifically, we could frame a socially authentic inquiry-based learning instruction placed in the students’ own community. For example, students could assess the risks of having a uranium pellet factory in their neighbourhood. Framing the question in terms of decision rather than opinion may give more weight to the project, and it could create an opportunity for students to reflect on the relationship between their values, mathematical and statistical thinking, and the content knowledge. To echo Monteiro and Ainley (2003), the pedagogical setting of the task would resemble the inquiry setting.

The study also showed an importance of representations in reasoning about risk that goes beyond verbal and formal-mathematical representations. For example, my findings show that students were very often using gestures in order to elucidate their arguments. Another potential direction would be to research students’ use of gestures and locate it within other research on students’ gestures in mathematics. The students were also making sense of the documents containing data, very often choosing data sources that presented data in visually accessible ways. Another potential research direction would be to study visualization of risk data most accessible to students in the classroom setting. As a starting point, the
research could apply existing research in the field of data visualization, such as that of Tufte (1997).

**Conclusion**

This research documents the complexity of the concept of risk and decision making based on risk. It also suggests how risk can be taught in the mathematics classroom. The study contributes to educational research by shedding light on the teaching and learning of risk in the mathematics classroom, whereas there is a lack of research in this area (Pratt et al., 2011). Another major contribution of the research is the identification of the understanding of rational numbers as being crucial to understanding risk.

An important lesson to take from my research is that decision making about risk is an interplay between quantitative reasoning, experiences, values, beliefs, and content knowledge. Restricting the instruction to any of these single components without meaningful consideration of other components will trivialize and reduce the effectiveness of the teaching. Risk is all around us and the pedagogy of risk should play an important role in mathematics education.
REFERENCES


Appendix A: Solution to the breast cancer problem by Eddy (1982)

To solve the following problem,

1% of women at age forty who participate in routine screening have breast cancer. 80% of women with breast cancer will get positive mammograms. 9.6% of women without breast cancer will also get positive mammograms. A woman in this age group had a positive mammogram in a routine screening. What is the probability that she actually has breast cancer?

Let A represent the event of having breast cancer; B the event of testing positive

We are given: \( P(A) = 0.01 \)

\[ P(B|A) = 0.8 \]

\[ P(B'|A') = 0.096 \]

We can calculate \( P(B) \) as follows:

\[ P(B) = P(B|A)P(A) + P(B|A')P(A') \]

\[ P(B) = 0.103 \]

We then substitute this value into the conditional probability formula:

\[ P(A|B) = \frac{P(B|A)P(A)}{P(B)} = \frac{(0.8)(0.01)}{1.094} = \frac{0.008}{1.094} = 0.0078 \]
Appendix B: Solution to the marble problem by Falk (1989)

Consider the following problem:

Two black marbles and two white marbles are put in an urn. We pick a marble at random from the urn. Then, without putting the marble in the urn again, we pick a second marble at random from the urn. The participants are then asked two questions:
1) If the first marble is white, what is the probability that this second marble is white;
2) If the second marble is white, what is the probability that the first marble is white.
(Falk, 1989)

The problem can be represented using the following tree diagram (B stands for the black marble, and W stands for the white one):

1) Given that the first marble was white, the probability that the second marble is white is 1/3, since we only have one white marble remaining and two black marbles
2) We know that the second marble was white. There are two ways that this could have happened:
1) The probability that first marble was white and the second marble was white = 
\[ \frac{2}{4} \times \frac{1}{3} = \frac{1}{6} \]

Or

2) The probability that first marble was black and the second marble was white

\[ \frac{2}{4} \times \frac{2}{3} = \frac{1}{3} \]

So the probability that the second marble was white is:

\[ \frac{1}{6} + \frac{1}{3} = \frac{1}{2} \]

However, the probability that the first marble was white given that the second marble was white is:

\[ P(\text{the first marble was white AND the second marble was white})/\]

\[ P(\text{the second marble was white})= \frac{\frac{1}{6}}{\frac{1}{2}} = \frac{1}{3} \]

The last result follows from the conditional probability formula.
Appendix C: Initial Assessment Questions

1) Do you agree or disagree with the following statement? Explain your reasoning.

“There have been around 500 nuclear power plants built since the 1950s. So far there have been only three significant nuclear power plant accidents. This makes nuclear power relatively safe compared to other means of generating power.”

2) Throughout this unit, we will use the knowledge of probability and statistics to try to determine how nuclear energy compares to other sources of energy in terms of safety. The reason why we chose this problem may be obvious to you: it is in the light of the Fukushima Daichi accident following the earthquake in Japan in March of this year.

In order to for us to see what the accident means to you, please answer the following background questions:

1. Write a paragraph on what you know about the accident.

2. What is your opinion on safety of nuclear power plants and how did the Fukushima incident influence your thinking?
Appendix D: Estimating probability of nuclear power plant accidents

(please list the names of people in the group)

Date:__________________________

Probability and Statistics Group Activity:

Estimating the probability of a nuclear accident.

Using the concept of empirical probability, we can try to estimate the probability of a nuclear accident.

First task is to determine how many accidents have occurred so far.

Here are some web sites that list the number of accidents:

http://www.world-nuclear.org/info/inf06.html (if you scroll down, they list three significant accidents)

http://archive.greenpeace.org/comms/nukes/chernob/rep02.html

http://www.guardian.co.uk/news/datablog/2011/mar/14/nuclear-power-plant-accidents-list-rank


You are also welcome to use any other web sites.

1) A) Which one of these lists have you decided to use? Why?

B) Which of these web sites is most reliable? Which one is the least reliable?

C) Did you include every incident mentioned? Why or why not?
D) What is the number of accidents that you have arrived at?

THE NUMBER OF ACCIDENTS =

2) Now that you have the number of accidents, what do we compare this to?

One possibility is to use the total number of nuclear power plants in operation. We could also take the total number of years that all of the reactors have been in operation.

We could find those at:

http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-world-wide.htm

TOTAL NUMBER OF ____________ (enter what you have used)

3) Combining data from 1) and 2), what is the probability that you have arrived at?

PROBABILITY OF A NUCLEAR ACCIDENT =

4) A) Do you think this number is small or large? Explain your reasoning.

   B) Based, on this number, could you improve your estimate?

   C) Based on the probability, would you think that the nuclear power plants are safe? Explain.
Appendix E1: The first data source: The World Nuclear Association Website
From: www.world-nuclear.org/info/inf06.html

Safety of Nuclear Power Reactors

(updated August 2013)

- From the outset, there has been a strong awareness of the potential hazard of both nuclear criticality and release of radioactive materials from generating electricity with nuclear power.
- As in other industries, the design and operation of nuclear power plants aims to minimise the likelihood of accidents, and avoid major human consequences when they occur.
- There have been three major reactor accidents in the history of civil nuclear power - Three Mile Island, Chernobyl and Fukushima. One was contained without harm to anyone, the next involved an intense fire without provision for containment, and the third severely tested the containment, allowing some release of radioactivity.
- These are the only major accidents to have occurred in over 14,500 cumulative reactor-years of commercial nuclear power operation in 32 countries.
- The risks from western nuclear power plants, in terms of the consequences of an accident or terrorist attack, are minimal compared with other commonly accepted risks. Nuclear power plants are very robust.

Context

In relation to nuclear power, Safety is closely linked with Security, and in the nuclear field also with Safeguards.

Some distinctions:

Safety focuses on unintended conditions or events leading to radiological releases from authorised activities. It relates mainly to intrinsic problems or hazards.

Security focuses on the intentional misuse of nuclear or other radioactive materials by non-state elements to cause harm. It relates mainly to external threats to materials or facilities.

Safeguards focus on restraining activities by states that could lead to acquisition of nuclear weapons. It concerns mainly materials and equipment in relation to rogue governments. (see also Safeguards paper)

Background

In the 1950s attention turned to harnessing the power of the atom in a controlled way, as demonstrated at Chicago in 1942 and subsequently for military research, and applying the steady heat yield to generate electricity. This naturally gave rise to concerns about accidents and their possible effects. However, with nuclear power safety depends on much the same factors as in any comparable industry: intelligent planning, proper design with conservative margins and back-up systems, high-quality components and a well-developed safety culture in operations.
A particular nuclear scenario was loss of cooling which resulted in melting of the nuclear reactor core, and this motivated studies on both the physical and chemical possibilities as well as the biological effects of any dispersed radioactivity. Those responsible for nuclear power technology in the West devoted extraordinary effort to ensuring that a meltdown of the reactor core would not take place, since it was assumed that a meltdown of the core would create a major public hazard, and if uncontained, a tragic accident with likely multiple fatalities.

In avoiding such accidents the industry has been very successful. In over 14,500 cumulative reactor-years of commercial operation in 32 countries, there have been only three major accidents to nuclear power plants - Three Mile Island, Chernobyl, and Fukushima - the second being of little relevance to reactor design outside the old Soviet bloc.

It was not until the late 1970s that detailed analyses and large-scale testing, followed by the 1979 meltdown of the Three Mile Island reactor, began to make clear that even the worst possible accident in a conventional western nuclear power plant or its fuel would not be likely to cause dramatic public harm. The industry still works hard to minimize the probability of a meltdown accident, but it is now clear that no-one need fear a potential public health catastrophe simply because a fuel meltdown happens. Fukushima has made that clear, with a triple meltdown causing no fatalities or serious radiation doses to anyone, while over two hundred people continued working on the site to mitigate the accident's effects.

The decades-long test and analysis program showed that less radioactivity escapes from molten fuel than initially assumed, and that most of this radioactive material is not readily mobilized beyond the immediate internal structure. Thus, even if the containment structure that surrounds all modern nuclear plants were ruptured, as it has been with at least one of the Fukushima reactors, it is still very effective in preventing escape of most radioactivity.

It is the laws of physics and the properties of materials that mitigate disaster, as much as the required actions by safety equipment or personnel. In fact, licensing approval for new plants now requires that the effects of any core-melt accident must be confined to the plant itself, without the need to evacuate nearby residents.

The three significant accidents in the 50-year history of civil nuclear power generation are:

- Three Mile Island (USA 1979) where the reactor was severely damaged but radiation was contained and there were no adverse health or environmental consequences
- Chernobyl (Ukraine 1986) where the destruction of the reactor by steam explosion and fire killed 31 people and had significant health and environmental consequences. The death toll has since increased to about 5
- Fukushima (Japan 2011) where three old reactors (together with a fourth) were written off and the effects of loss of cooling due to a huge tsunami were inadequately contained.

A table showing all reactor accidents, and a table listing some energy-related accidents with multiple fatalities are appended.
These three significant accidents occurred during more than 14,500 reactor-years of civil operation. Of all the accidents and incidents, only the Chernobyl and Fukushima accidents resulted in radiation doses to the public greater than those resulting from the exposure to natural sources. The Fukushima accident resulted in some radiation exposure of workers at the plant, but not such as to threaten their health, unlike Chernobyl. Other incidents (and one 'accident') have been completely confined to the plant.

Apart from Chernobyl, no nuclear workers or members of the public have ever died as a result of exposure to radiation due to a commercial nuclear reactor incident. Most of the serious radiological injuries and deaths that occur each year (2-4 deaths and many more exposures above regulatory limits) are the result of large uncontrolled radiation sources, such as abandoned medical or industrial equipment. (There have also been a number of accidents in experimental reactors and in one military plutonium-producing pile - at Windscale, UK, in 1957, but none of these resulted in loss of life outside the actual plant, or long-term environmental contamination.) See also Table 2 in Appendix.
Appendix E2: Greenpeace: Calendar of nuclear events
From: http://pec.putney.net/issue_detail.php?ID=18

365 days of the year Greenpeace has tallied up a Calendar of Nuclear Accidents

Subject: Calendar of Nuclear Accidents and Events
(Updated March 26th 2010)

Calendar of Military Nuclear Accidents
Below is a calendar that shows the threat that humanity faces from the atom bomb and the nuclear fuel cycle. This calendar gives some examples of the everyday nuclear incidents that have occurred all over the world. It demonstrates how technological failures coupled with human error risk public health and the environment on an almost daily basis.

January
1-1992: Four tons of heavy water spilt at Rajasthan nuclear power plant (India)
2-1993: Leak at Kozloduy nuclear power plant, release of radioactive steam (Bulgaria)
3-1961: Explosion in reactor Idaho Falls (USA); three people killed
4-1965: 6.5 kg plutonium sludge released from Savannah River reprocessing plant (USA)
5-1976: Two workers killed by radioactive carbon dioxide at Bohunice nuclear power plant (Slovakia)
6-1981: Accident at La Hague reprocessing plant (France)
6-2010: Energy Vermont announces Tritium leak at VY
7-1974: Explosion at Leningrad nuclear power plant (Russia)
8-1975: Release of radioactivity from Mihama nuclear power plant (Japan)
9-1993: Radioactive release from leaking fuel rods at Perry nuclear power plant (USA)
10-1987: Nuclear transport accident in the UK
11-1985: In Heilbronn (Germany), a Pershing-II nuclear missile catches fire, three people killed
12-1960: Technicians trying to restart a reactor at Savannah River reprocessing plant almost send it out of control (USA)
13-1964: A B-52 plane crashes with nuclear bombs on board in Maryland (USA)
14-1969: USS Enterprise, nuclear aircraft-carrier, suffers fires and explosions, killing 28 crew members
15-
16-1990: Loss of offsite power with multiple equipment failures at Dresden nuclear power plant (USA)
17-1966: A B-52 plane crashes in Spain causing plutonium contamination
18-1989: Eight workers are contaminated at Savannah River reprocessing plant (USA)
19-1992: Radioactive leak, reactor shut-down at Kola nuclear power plant (Russia)
20-1993: Technical failure at Paluel causes subcooling accident (France)
21-1969: Technical failure at Swiss experimental nuclear reactor causes release of radioactive water
22-1992: Technical failure in shut-down system at Balakovo nuclear power plant
(Russia)
23-1978: Radioactive helium released from Colorado reactor (USA)
24-1978: Soviet nuclear-powered satellite Cosmos-954 crashes in Canada
25-1982: Steam generator ruptures at R.E. Ginna nuclear power plant (USA)
26-1988: Dangerous temperature rise in a nuclear reactor on board a British submarine
27-1992: Leak causes a shut-down at Darlington nuclear power plant (Canada)
28-1990: Pump failure during a shut-down at Gravelines nuclear power plant (France)
29-1961: A B-52 plane carrying nuclear bombs crashes, the bombs do not explode but three of the eight crew members are killed (USA)
30-
31 -1996: Leakage of radiation due to human error and technical failure at Dimitrovgrad nuclear research centre (Russia)

February
1-1982: Release of 100 cubic metres of radioactive water from Salem nuclear power plant (USA)
2-1993: Breakdown of cooling system for two hours at Kola nuclear power plant (Russia)
2-2002: Davis Besse incomplete cleaning and removal of boric acid from system leads to extreme corrosion leaving only a thin layer standing between the 2400 psi pressure of the primary cooling system and the 14 psi atmospheric pressure containment. Near Miss!
3-1992: Failure of cooling pumps at Kozloduy nuclear power plant (Bulgaria)
4-
5-1986: "Amber alert" (indicating an emergency in one building and a threat to the rest of the plant)" at Sellafield reprocessing plant, UK
6-1974: Explosion and radiation leak at Leningrad nuclear power plant, three people killed (Russia)
6-2005: Entergy reports leak at VY plant in Vermont
7-
8-1991: Release of radioactivity from Fukui nuclear power plant (Japan)
9-1991: Rupture of steam generator pipe causes release of radioactivity at Mihama nuclear power plant (Japan)
10-1992: Technical failure in pump system at Zaporozhe nuclear power plant (Ukraine)
11-1986: Release of 13 tonnes of radioactive carbon dioxide from Transfynydd nuclear power plant (UK)
12-1968: A B-52 plane with nuclear bombs on board crashes near Toronto (Canada)
13-1980: A brief power excursion in Reactor A2 led to a rupture of fuel bundles and a minor release (8 x 1010 Bq) of nuclear materials at the Saint-Laurent Nuclear Power Plant. The reactor was repaired and continued operation until its decommissioning in 1992.
15-1993: Spillage of 18,000 litres of heavy water at Darlington nuclear power plant (Canada)
16-1973: Container filled with Cobalt-60 lost in the North Sea
17-1984: Accident at Kozloduy nuclear power plant (Bulgaria)
18-1988: Report of core melt in the nuclear reactor of the Soviet Ice-Breaker "Rossiya"
19-1986: Three workers suffer contamination at the Sellafield reprocessing plant (UK)
20-1990: Eight employees receive radiation exposure at Point Lepreau (Canada)
21-1976: Accident at Bohunice nuclear power plant (Slovakia)
22-1993: High pressure steam accident kills one worker and injures two others at Fukushima nuclear power plant (Japan).
22-1977: Jaslovské Bohunice, Czechoslovakia - Fuel damaged. Operators neglected to remove moisture absorbing materials from a fuel rod assembly before loading it into the KS 150 reactor at power plant A-1. The accident resulted in damaged fuel integrity, extensive corrosion damage of fuel cladding and release of radioactivity into the plant area. The plant was decommissioned following this accident.
23-1981: Accidental explosion of a Pershing-II missile in Germany
24-1972: Accident on board Soviet nuclear-powered submarine causes vessel to lose all power
25-1983: Failure of automatic shut-down at Salem nuclear power plant (USA)
26-1988: Increased levels of radioactivity at Bohunice nuclear power plant (Slovakia)
27-1983: Nuclear powered satellite falls into the Indian Ocean
28-1979: Middletown, Dauphin County, Pennsylvania, United States - Partial meltdown! Equipment failures and worker mistakes contributed to a loss of coolant and a partial core meltdown at the Three Mile Island Nuclear Generating Station 15 km (9 miles) southeast of Harrisburg. While the reactor was extensively damaged on-site radiation exposure was under 100 millirems (less than annual exposure due to natural sources), with exposure of 1 millirem (10 µSv) to approximately 2 million people. There were no fatalities. Follow up radiological studies predict at most one long-term cancer fatality.
February 2003: Oak Ridge, Tennessee Y-12 facility. During the final testing of a new saltless uranium processing method, there was a small explosion followed by a fire. The explosion occurred in an unvented vessel containing unreacted calcium, water and depleted uranium. An exothermic reaction among these articles generated enough steam to burst the container. This small explosion breached its glovebox, allowing air to enter and ignite some loose uranium powder. Three employees were contaminated. BWXT, a partnership of BWX Technologies and Bechtel National, was fined $82,500 for the accident.
March
1-1954: Fall-out of US nuclear weapons test "Bravo" contaminates the inhabitants of the Pacific island of Rongelap.
2-1994: Breakdown of cooling system at Kola nuclear power plant (Russia)
3-1992: Technical failure at Novovoronezh nuclear power plant (Russia)
4-1977: Kozloduy nuclear power plant affected by an earthquake (Bulgaria)
5- 6-1985: Emergency cooling system out of order at the Grohnde nuclear power plant (Germany)
6-2006: Erwin, Tennessee, United States - Nuclear material leak. Thirty-five liters of a highly enriched uranium solution leaked during transfer into a lab at Nuclear Fuel Services Erwin Plant. The incident caused a seven-month shutdown. A required public hearing on the licensing of the plant was not held due to the absence of public notification
7-
8-1972: Radioactive water has to be pumped out of the Indian Point nuclear power plant (USA)
9-1992: Fire at Kola nuclear power plant (Russia)
10-1956: A B-47 plane disappears with nuclear weapons on board in the Atlantic Ocean
11-1958: A B-47 plane loses nuclear bomb in South Carolina (USA)
12-1981: Tornado washes nuclear waste from Moruroa into the lagoon (Pacific)
13-1986: US nuclear submarine runs aground and suffers damage
14-1961: A B-52 plane crashes with nuclear bombs on board in California (USA)
15-1989: Technical failure of fuel roads at Pickering nuclear power plant (Canada)
16-
17-1984: Emergency cooling system at San Onofere nuclear power plant fails (USA)
18-1987: Fire and release of radioactivity at Australian nuclear research facility
19-
20-1977: Temperature increase at Rancho Seco nuclear power plant (USA)
21-1984: Soviet nuclear submarine collides with US aircraft carrier "Kitty Hawk"
22-1975: Fire in reactor at Browns Ferry nuclear power plant (USA)
23-
24-1992: Incident with radiation leakage, shut-down of reactor at Leningrad nuclear power plant (Russia)
25-1992: Technical failure at Leningrad nuclear power plant (Russia)
26-1991: Refuelling accident at Wuergassen nuclear power plant (Germany)
27-
28-1979: Partial core meltdown at Three Mile Island nuclear power plant (USA)
29-1992: Failure of shut-down system at Ignalina nuclear power plant (Lithuania)
30-
31-1992: Automatic shut-down due to failure of pump system at Kalinin nuclear power plant (Russia)

April
1-1989: Control rod failure at Gravelines nuclear power plant (France)
2-1979: Two workers suffer radioactive contamination at Tokaimura nuclear complex (Japan)
3-1960: Melting of fuel elements cause a release of radioactivity at the Test Reactor at Waltz Mills (USA)
4-
5-
6-1993: Explosion at the Tomsk-7 nuclear complex (Russia) A pressure buildup led
to an explosive mechanical failure in a 34 cubic meter stainless steel reaction vessel buried in a concrete bunker under building 201 of the radiochemical works at the Tomsk-7 Siberian Chemical Enterprise plutonium reprocessing facility. The vessel contained a mixture of concentrated nitric acid, uranium (8757 kg), plutonium (449 g) along with a mixture of radioactive and organic waste from a prior extraction cycle. The explosion dislodged the concrete lid of the bunker and blew a large hole in the roof of the building, releasing approximately 6 GBq of Pu 239 and 30 TBq of various other radionuclides into the environment. The contamination plume extended 28 km NE of building 201, 20 km beyond the facility property. The small village of Georgievka (pop. 200) was at the end of the fallout plume, but no fatalities, illnesses or injuries were reported. The accident exposed 160 on-site workers and almost two thousand cleanup workers to total doses of up to 50 mSv (the threshold limit for radiation workers is 100 mSv per 5 years)

7-1992: Failure of automatic shut-down system at Novovoronezh nuclear power plant (Russia)
8-1989: Soviet nuclear submarine "Komsomolets" sinks off Norway
10-1963: US-nuclear submarine sinks with 123 crew members in the Atlantic
10-2003: Hungary - Fuel damaged, Partially spent fuel rods undergoing cleaning in a tank of heavy water ruptured and spilled fuel pellets at Paks Nuclear Power Plant. It is suspected that inadequate cooling of the rods during the cleaning process combined with a sudden influx of cold water thermally shocked fuel rods causing them to split. Boric acid was added to the tank to prevent the loose fuel pellets from achieving criticality.
11-1950: A B-29 plane crashes in New Mexico, thirteen people killed.
12-1970: Soviet nuclear submarine sinks in the Atlantic
13-1979: Fire in the generator of the Baersbeck nuclear power plant (Sweden)
14-1970: Soviet nuclear submarine sinks with 52 crew members in Indian ocean
15-1983: Incident at Turkey Point nuclear power plant (USA)
16-1992: Technical failure of reactor shut-down system at Kola nuclear power plant (Russia)
17-1970: Incident involving a vehicle at a French nuclear test site in the South Pacific causes a plutonium spillage into the ocean.
18-1992: Technical failure during refuelling at Kola nuclear power plant (Russia)
19-1984: Technical failure at Sequoyah nuclear power plant causes spillage of radioactive coolant water. (USA)
19-2005: Sellafield, England, United Kingdom - Nuclear material leak. Twenty metric tons of uranium and 160 kilograms of plutonium dissolved in 83,000 litres of nitric acid leaked over several months from a cracked pipe into a stainless steel sump chamber at the Thorp nuclear fuel reprocessing plant. The partially processed spent fuel was drained into holding tanks outside the plant.
20-1973: Thousands of cubic meters of radioactive waste flow out of Hanford nuclear weapons complex (USA)
21-1964: US-satellite disperses 1.2 kg plutonium into the atmosphere.
22-1983: Reactor shut-down due to failure of fuel rods at Kursk nuclear power plant (Russia)
23-1991: Lost of offsite power cause technical failure at "Vermont Yankee" nuclear submarine (USA)
24-
25-1990: Flooding of building due to increase of coolant level at Bohunice nuclear power plant (Slovakia)
26-1986: Explosion of reactor 4 at Chernobyl nuclear power plant; the worst civilian nuclear accident to date.
A mishandled reactor safety test led to an uncontrolled power excursion, causing a severe steam explosion, meltdown and release of radioactive material at the Chernobyl nuclear power plant located approximately 100 kilometers north-northwest of Kiev. Approximately fifty fatalities (mostly cleanup personnel) resulted from the accident and the immediate aftermath. An additional nine fatal cases of thyroid cancer in children in the Chernobyl area have been attributed to the accident. The explosion and combustion of the graphite reactor core spread radioactive material over much of Europe. 100,000 people were evacuated from the areas immediately surrounding Chernobyl in addition to 300,000 from the areas of heavy fallout in Ukraine, Belarus and Russia. An "Exclusion Zone" was created surrounding the site encompassing approximately 1,000 m² (3,000 km²) and deemed off-limits for human habitation for an indefinite period. Several studies by governments, UN agencies and environmental groups have estimated the consequences and eventual number of casualties. Their findings are subject to controversy.
27-
28-1988: Release of 5000 Curies of tritium gas from the Bruyere le Chatel military nuclear complex (France)
29-1986: US-nuclear submarine "Atlanta" hits the ground off Gibraltar
30-1992: Breakdown of cooling system at Novovoronezh nuclear power plant (Russia)

May

1-1992: Technical failure at Ignalina nuclear power plant (Lithuania)
2-1979: Technical fault at the Oyster Creek nuclear power plant triggers emergency shut-down (USA)
3-1974: Leakage at Hanford nuclear weapons complex (USA)
4-1986: Release of radiation from Hamm-Uentrop nuclear power plant (Germany), A spherical fuel pebble became lodged in the pipe used to deliver fuel elements to the reactor at an experimental 300-megawatt THTR-300 HTGR. Attempts by an operator to dislodge the fuel pebble damaged its cladding, releasing radiation detectable up to two kilometers from the reactor
5-1987: Pershing nuclear missile ends up in a ditch after a transport accident at Heilbronn (Germany)
6-1989: Fire of pump equipment at Bohunice nuclear power plant (Slovakia)
7-1992: Failure of emergency system at Smolensk nuclear power plant (Russia)
8-1964: First Chinese nuclear test
9-1992: Technical failure of cooling system at Hatch nuclear power plant (USA)
9-2008: Entergy Nuclear admits to a failure to monitor high level radiation at on site dry casks.
10-1965: Release of eight cubic metres of cooling water from Savannah River
reprocessing plant (USA)
11-1969: Fire at Rocky Flats nuclear weapons plant causes plutonium to spontaneously ignite. (USA)
12-1984: Uncontrolled power surge at Bohunice nuclear power plant (Slovakia)
13-1992: Tube leak causes a radioactive release of 12 Curies of radioactivity from Tarapur nuclear power station (India)
14-1986: The power lines to the Palo Verde nuclear power plant are sabotaged (USA)
15-16-1992: Reactor shut-down at Kola nuclear power plant (Russia)
17-1984: Fire on board the US-nuclear submarine "Guitarro"
18-1968: Accident during launch of US satellite, radioactive materials fall into ocean near California coast
19-
20-1974: First Indian nuclear test, also 1978: Rancho Seko near miss
21-1968: US-nuclear submarine "Scorpion" sinks off the Acores, 99 people die
22-1957: Human error causes a B-36 plane to release a nuclear bomb in New Mexico
22-1975: Browns Ferry Unit 1 fire
23-1958: Accident and release of radioactivity at the Chalk River experimental reactor (Canada)
24-1968: Incident on board of Soviet nuclear submarine "K-27", 5 crew members killed by radiation release
25-
26-1990: During refuelling, five cubic meters of radioactive water spilled at the Fessenheim nuclear power plant (France)
27-1993: Reactor shut-down due to breakdown of cooling system at Kola nuclear power plant (Russia)
28-1970: Collision of the US-nuclear submarine "Daniel Boone".
28-1979: Three Mile Island accident
29-
30-
31-

June
1-1991: Failure of core cooling system at Belleville nuclear power plant (France)
2-1992: Total failure of centralised control system at the Smolensk nuclear power plant (Russia)
3-1980: Computer fault causes full-scale alert for US Military Strategic Command
4-1989: Fire in the cables of the cooling pumps at the Bohunice nuclear power plant (Slovakia)
5-1989:
6-1994: Fire at Beloyarsk nuclear power plant (Russia)
7-1960: Fire in a BOMARC-rocket in New Jersey causes plutonium release into the atmosphere (USA)
8-1992: Failure of cooling system at Kola nuclear power plant (Russia)
9-1985: Malfunction in the cooling system at Davis Blesse nuclear power plant (USA)
10-1985: Collision of a British nuclear submarine off the coast of Florida (USA)
11-1989: Spent fuel element dropped in the storage pool and damaged at Kruemmel nuclear power plant (Germany)
12-
13-
14-
15-1992: Technical failure at Sizewell nuclear power plant (UK)
16-1988: Technical failure at Zorita nuclear power plant (Spain)
17-1967: First Chinese hydrogen nuclear bomb test
18-1978: Release of two tons of radioactive steam from Brunsbuettel nuclear power plant (Germany)
18-2004: Transformer Fire at Vermont Yankee
19-1992: Leak in pipe conducting sea water to cooling system at Leningrad nuclear power plant (Russia)
20-1985 Collision of two trucks carrying nuclear bombs in Scotland (UK)
21-
22-
23-1986: Twelve people receive 'slight' plutonium contamination while inspecting a store room at Tokaimura nuclear complex (Japan)
24-1992: Technical failure of control system at Leningrad nuclear power plant (Russia)
25-
26-1989: Fire and reactor damage in a Soviet submarine
27-1985: Explosion and steam leakage killed 14 workers at Balakovo nuclear power plant (Russia)
28-
29-1991: Power limited due to error between actual and indicated power at Pickering nuclear power plant (Canada).
30-1983: Total loss of coolant at Embalse nuclear power plant (Argentina)
Ishikawa Prefecture, Japan - Control rod malfunction
Operators attempting to insert one control rod during an inspection neglected procedure and instead withdrew three causing a 15 minute uncontrolled sustained reaction at the number 1 reactor of Shika Nuclear Power Plant. The Hokuriku Electric Company who owned the reactor did not report this incident and falsified records, covering it up until March, 2007.

July
1-1983: Technical failure causes release of Iodine-131 from Phillipsburg nuclear power plant (Germany)
2-1966: French nuclear testing in the South Pacific begins
3-1981: Fire at North Anna nuclear power plant (USA)
4-1961: Incident on board of Soviet nuclear submarine "K-19", radiation release kills 9 crew members
5-
6-1959: US plane carrying nuclear weapons crashes and catches on fire
7-
8-
9-1991: Flaw in cooling system at Wurgassen nuclear power plant (Russia)
10-1991: Leakage of radiation at Bilibino nuclear power plant (Russia)
11-12-1993: Failure of control system at Susquehanna nuclear power plant (USA)
13-14-1992: Reactor shut-down due to failure of cooling system at Novovoronezh nuclear power plant (Russia)
15-16-1945: First explosion of a nuclear bomb ("Trinity") in New Mexico (USA)
17-1991: Reactor shut-down due to break of control system at Sendai nuclear power plant (Japan)
18-1991: Steam leakage causes reactor shut-down at Paks nuclear power plant (Hungary)
19-20-1992: Leakage of radiation due to breakdown of cooling system at Ignalina nuclear power plant (Lithuania)
21-22-1992: Two workers contaminated at Dampierre nuclear power plant (France)
23-24-1989: Refuelling accident at Isar nuclear power plant (Germany)
25-1946: US nuclear test "Baker" causes unexpected plutonium contamination on target vessels
26-1992: Temperature rise in storage pool at Gravelines nuclear power plant (France)
27-1956: US plane crashes into nuclear ammunition storage in the UK
28-1957: US plane loses two nuclear bombs in the Atlantic
29-
30-1986: Human error causes the nuclear warhead to be knocked off a Pershing rocket (Germany)
31-1993: Refuelling machine malfunctions at the Wylfa nuclear power plant (UK)

August
1-1983: An engineer receives a fatal radiation dose at a research reactor in Argentina
2-1987: Elevated radiation level after Soviet nuclear test
3-1983: Argentinean engineer dies from radiation dose received two days earlier
4-5-1950: B-29 plane with nuclear weapons on board crashes; 19 people killed (USA)
6-1945: Nuclear bomb dropped on the Japanese city of Hiroshima
7-
8-
9-1945: Nuclear bomb dropped on the Japanese city of Nagasaki
10-1985: Explosion on board a Soviet nuclear submarine
11-1988: Damage detected at Atucha nuclear power plant (Argentina)
12-
13-
14-1989: Instrumentation and control failure at Grand Gulf nuclear power plant (USA)
15-1992:
16-1991: Eight control rods show delays in emergency shut-down insertion time at
Millstone Point nuclear power plant (USA)
17-1991: Automatic shut-down due to technical problems at Sendai nuclear power plant (Japan)
18-1953: First explosion of Soviet hydrogen bomb
19-1986: Flooding at the Cattenom nuclear power plant (France)
20-1974: Incident at Beznau nuclear power plant (Switzerland)
21-1980: Accident on board Soviet nuclear submarine, believed to kill at least nine crew members.
22-1992: Failure of shut-down system at Novovoronezh nuclear power plant (Russia)
23-
24-
25-1984: French freighter sinks in the English Channel with 375 tonnes of uraniumhexafluoride on board
26-1989: Technical failure at Ignalina nuclear power plant (Lithuania)
27-1990: Cable fire causes loss of control of the position of control rods at Chernobyl nuclear power plant (Ukraine)
28-1992: Fire in electro-generator at St. Alban nuclear power plant (France)
29-1949: First explosion of Soviet atomic bomb
30-1985: Fire in a barrel of radioactive waste at Karlsruhe nuclear complex (Germany)
31-1985: Fire at Fukushima nuclear power plant during routine shut-down (Japan)

September
1-1993: Fire at Balakovo nuclear power plant (Russia)
2-
3-1974: Release of radioactive water at Los Alamos nuclear weapons Laboratory (USA)
4-1988: Fire at Perry nuclear power plant (USA)
5-1988: Fire at Ignalina nuclear power plant (Lithuania)
6-1991: Incident and steam leak during refueling at Barsebeck nuclear power plant (Sweden)
7-
8-
9-1989: Control rod failure at Olkiluoto nuclear power plant (Finland)
10-
11-1957: 15 kgs of plutonium catch fire at Rocky Flats nuclear weapons complex (USA)
12-1992: Leakage of radioactive water at Kola nuclear power plant (Russia)
13-1987: 249 people are contaminated in Brazil, due to handling discarded nuclear medical equipment, four people subsequently die
14-1991: Leakage at Kozloduy nuclear power plant (Bulgaria)
15-1986: Fire on board a US plane carrying nuclear weapons
16-1990: Superphenix Fast Breeder Reactor is closed down due to technical failures (France)
17-1988: Nuclear weapons convoy road accident kills one person (UK)
18-1988: Technical failure at Stade nuclear power plant (Germany)
19-1984: Collision of a Soviet nuclear submarine
20-1977: US-nuclear submarine "Ray" hits the sea-bed, three crew members are injured
21-1989: Manual shut-down of WNP nuclear power plant (USA)
22-1980: Pump failure causes accidental release of radioactive water at La Hague reprocessing plant (France)
23-1983: Buenos Aires, Argentina - Accidental release. An operator error during a fuel plate reconfiguration in an experimental test reactor led to an excursion of $3 \times 10^{17}$ fissions at the RA-2 facility. The operator absorbed 2000 rad (20 Gy) of gamma and 1700 rad (17 Gy) of neutron radiation which killed him two days later. Another 17 people outside of the reactor room absorbed doses ranging from 35 rad
24-1973: 35 workers at the Sellafield reprocessing plant are contaminated following a technical failure (UK)
25-1955: First Soviet underwater nuclear explosion near Novaya Zemlya (Arctic Ocean)
28-1990: Cables for reactor control and protection system supply overheat at Bohunice nuclear power plant (Slovakia)
29-1957: Thousands of square miles contaminated by accident at the Chelyabinsk nuclear complex (Russia)
30-1990: Failure of reactor core cooling system at Palisades nuclear power plant (USA).
30-1999: Ibaraki Prefecture, Japan - Accidental. Workers put uranyl nitrate solution containing about 16.6 kg of uranium, which exceeded the critical mass, into a precipitation tank at a uranium reprocessing facility in Tokai-mura northeast of Tokyo, Japan. The tank was not designed to dissolve this type of solution and was not configured to prevent eventual criticality. Three workers were exposed to (neutron) radiation doses in excess of allowable limits. Two of these workers died. 116 other workers received lesser doses of 1 mSv or greater though not in excess of the allowable limit.

October
1-1983: Technical failure and human error cause accident at Blayas nuclear power plant (France)
2-1968: Leakage at La Hague reprocessing plant (France) 3-1952: First UK nuclear test
4-1981: Release of 300-times the normal discharge level of Iodine-131 at Sellafield reprocessing plant (UK)
5-1966: Partial core meltdown at the Fermi fast breeder reactor (USA)
6-1986: Soviet nuclear submarine sinks off the coast of Bermuda
7-1984: Emergency shut-down of Paks nuclear power plant (Hungary)
8-1985: Accidental radioactive release into the sea from Hinkley Point nuclear power station (UK)
9-1991: Technical failure at Yugno-Ukrainskaya nuclear power plant (Ukraine)
10-1957: Three tonnes of uranium catch fire at the Windscale reprocessing plant (now Sellafield UK)
11-1957: US nuclear bomber crashes in Florida and catches fire
12-13-1977: Sea water runs into the cooling circuit of Hunterston nuclear power plant (UK)
14-1953: Fall-out from British nuclear test "Totem" contaminates Aborigines in the Australian desert
15-1988: French officials carry out an experiment to test the effects of releasing 7000 Curies of radioactivity
16-1964: First Chinese nuclear test
17-1969: Fuel elements melt at St Laurent des Eaux nuclear power plant (France)
18-1991: Technical failure at Zaporozhe nuclear power plant (Ukraine)
19-1991: Offsite power failure at Smolensk nuclear power plant (Russia)
20-2008: Twenty-five workers on the top floor of the reactor building at the Vermont Yankee nuclear power plant had to be evacuated Monday night after the top of the reactor vessel was placed too close to a fan, which distributed unsafe levels of radiation.(US)
21-1991: Fire on board "Sceptre" nuclear submarine in Scotland
22-1993: Instrumentation and Control failure at Saint Alban nuclear power plant (France)
23-1989: Failure of core cooling system at Dresdan nuclear power plant (USA)
24-
25-1991: Failure of shut-down system during refuelling at Novovoronezh nuclear power plant (Russia)
26-1991: Incident during refueling at Vogtle nuclear power plant (USA)
27-1991: Technical failure of shut-down system at Zaporozhe nuclear power plant (Ukraine)
28-
29-1991: Technical failure causes automatic shut-down at Kalinin nuclear power plant (Russia)
30-1991:
31-1986: US-nuclear submarine "Augusta" involved in collision

November
1-1992: Cracks in cooling system equipment at Brunsbuttel nuclear power plant (Germany)
2-1982: Nuclear missile transporter crashes killing one person and injuring two others (Germany)
3-1990: Failure of core cooling equipment at Doel nuclear power plant (Belgium)
4-1970: Explosion on board a nuclear-capable US-destroyer kills two sailors
5-1967: UK nuclear-powered ballistic missile submarine `HMS Repulse' runs aground 30 minutes after its launch
6-
7-1967: Release of radioactivity at Grenoble nuclear power plant (France)
8-
9-1955: Core meltdown at EBR fast breeder reactor (USA)
10-
11-1988: Accident during refueling on board of Soviet nuclear powered ice-breaker "Lenin"
12-1993: London Convention bans the dumping of nuclear waste into the sea
13-1974: Karen Silkwood, a worker at a US nuclear plant, dies mysteriously on her way to hand important documents to a Trade Union Official and a journalist
14-1989: Breakdown of fuel rod control system at Oconee nuclear power plant (USA)
15-1989: Fire on board US-nuclear submarine "Finback"
16-1983: Sellafield reprocessing plant discharges highly radioactive wastes directly into the sea (UK)
17-18-1991: Reactor shut-down due to technical failure at Balakovo nuclear power plant (Russia)
20-1989: Fire in turbine equipment at Kozloduy nuclear power plant (Bulgaria)
21-
22-
23-1991: Leak of 190,000 litres of water from cooling system, reactor shut-down at Oconee nuclear power plant (USA)
24-1989: Technical failure nearly causes core meltdown at Greifswald nuclear power plant (Germany), Operators disabled three of six cooling pumps to test emergency shutoffs. Instead of the expected automatic shutdown a fourth pump failed causing excessive heating which damaged ten fuel rods. The accident was attributed to sticky relay contacts and generally poor construction in the Soviet-built reactor.
25-1991: Failure of cooling system causes automatic reactor shut-down at Kursk nuclear power plant (Russia)
26-1958: B-47 plane catches fire, destroying one nuclear weapon (USA)
27-1991: Disfunction of automatic shut-down system at Bilibino nuclear power plant (Russia)
28-1991: Failure of control system causes reactor shut-down at Kursk nuclear power plant (Russia)
30-1975: 1.5 million Curies released from Leningrad nuclear power plant (Russia)

December
1-1991: Technical failure at Beloyarsk nuclear power plant (Russia)
2-1949: US experiment "Green Run" contaminates communities up to 70 miles away from the Hanford nuclear weapons complex (USA)
3-1988: Explosion at the Burghfield Atomic Weapons Establishment (UK)
4-1990: 2 workers irradiated during refuelling at Blayais nuclear power plant (France)
5-1965: Plane crashes with nuclear bombs on board off the coast of Japan
6-1991: Failure of control system during refuelling causes reactor shut-down at Smolensk nuclear power plant (Russia)
7-1991: Failure of cooling system at Kola nuclear power plant (Russia)
8-1995: Fire due to leakage of sodium coolant from Monju fast breeder reactor, Japanese nuclear industry attempts to cover up full extent of accident, reactor shut-down
9-1986: Explosion at Surry nuclear power plant, four people killed (USA).
10-1991: Failure of turbo-generator causes reactor shut-down at Balakovo nuclear power plant (Russia)
11-1991: Human error causes failure of automatic reactor shut-down equipment at Kola nuclear power plant (Russia)
12-1952: World's first major nuclear reactor disaster, Chalk River experimental reactor (Canada)
13-1988: Four of the eight emergency installations discovered out of order at Brokdorf nuclear power plant (Germany)
14-1991: Technical failure causes automatic shut-down at Balakovo nuclear power plant (Russia)
15-1991: Technical failure at Kalinin nuclear power plant (Russia)
16-1991: Technical failure at Kola nuclear power plant (Russia)
17-1987: Severe incident at Biblis nuclear power plant (Germany)
18-1984: Fire at Kalinin nuclear power plant (Russia)
19-1980: Plutonium transport accident in the USA
20-1990: Control element discovered damaged at Novovoronezh nuclear power plant (Russia)
21-1991: Radiation leakage at Kolskaya nuclear power plant (Russia)
22-1987: Accidental release of 50 tonnes of water from Atucha nuclear power plant (Argentina)
23-1988: Two control rods jammed at Blayais nuclear power plant (France)
24-1991: Reactor shut-down due to technical failure at Kalinin nuclear power plant (Russia)
25-1992: Radioactive water leakage at Beloyarsk nuclear power plant (Russia)
26-
27-1991: Automatic shut-down Balakovo nuclear power plant (Russia)
28-1990: Incident and radiation leakage at Leningrad nuclear power plant (Russia)
29-
30-1988: Reactor shut-down due to failure of control equipment at Pilgrim nuclear power plant (USA)
31-1978: Fire and loss of reactor control, 8 workers irradiated at Beloyarsk nuclear power plant (Russia)
Appendix E3: Guardian Website
From http://www.theguardian.com/news/datablog/2011/mar/14/nuclear-power-plant-accidents-list-rank#data

Nuclear power plant accidents: listed and ranked since 1952

How many nuclear power plants have had accidents and incidents? Get the full list and find out how they're ranked

Nuclear power plant accidents: Number three reactor of the Fukushima nuclear plant is seen burning after a blast following an earthquake and tsunami Photograph: Ho/DigitalGlobe

power station accidents and incidents

Click heading to sort table.

<table>
<thead>
<tr>
<th>Year</th>
<th>Incident</th>
<th>INES level</th>
<th>Country</th>
<th>IAEA description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Fukushima</td>
<td>5</td>
<td>Japan</td>
<td>Reactor shutdown after the 2011 Sendai earthquake and tsunami; failure of emergency cooling caused an explosion</td>
<td></td>
</tr>
<tr>
<td>2011 Onagawa</td>
<td>Japan</td>
<td>Reactor shutdown after the 2011 Sendai earthquake and tsunami caused a fire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006 Fleurus</td>
<td>4</td>
<td>Belgium</td>
<td>Severe health effects for a worker at a commercial irradiation facility as a result of high doses of radiation</td>
<td></td>
</tr>
<tr>
<td>2006 Forsmark</td>
<td>2</td>
<td>Sweden</td>
<td>Degraded safety functions for common cause failure in the emergency power supply system at nuclear power plant</td>
<td></td>
</tr>
<tr>
<td>2006 Erwin</td>
<td>US</td>
<td></td>
<td>Thirty-five litres of a highly enriched uranium</td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>Incident</td>
<td>INES level</td>
<td>Country</td>
<td>IAEA description</td>
</tr>
<tr>
<td>-------</td>
<td>------------------</td>
<td>------------</td>
<td>------------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2005</td>
<td>Sellafield</td>
<td>3</td>
<td>UK</td>
<td>Release of large quantity of radioactive material, contained within the installation</td>
</tr>
<tr>
<td>2005</td>
<td>Atucha</td>
<td>2</td>
<td>Argentina</td>
<td>Overexposure of a worker at a power reactor exceeding the annual limit</td>
</tr>
<tr>
<td>2005</td>
<td>Braidwood</td>
<td>US</td>
<td></td>
<td>Nuclear material leak</td>
</tr>
<tr>
<td>2003</td>
<td>Paks</td>
<td>3</td>
<td>Hungary</td>
<td>Partially spent fuel rods undergoing cleaning in a tank of heavy water ruptured and spilled fuel pellets</td>
</tr>
<tr>
<td>1999</td>
<td>Tokaimura</td>
<td>4</td>
<td>Japan</td>
<td>Fatal overexposures of workers following a criticality event at a nuclear facility</td>
</tr>
<tr>
<td>1999</td>
<td>Yanangio</td>
<td>3</td>
<td>Peru</td>
<td>Incident with radiography source resulting in severe radiation burns</td>
</tr>
<tr>
<td>1999</td>
<td>Ikitelli</td>
<td>3</td>
<td>Turkey</td>
<td>Loss of a highly radioactive Co-60 source</td>
</tr>
<tr>
<td>1999</td>
<td>Ishikawa</td>
<td>2</td>
<td>Japan</td>
<td>Control rod malfunction</td>
</tr>
<tr>
<td>1993</td>
<td>Tomsk</td>
<td>4</td>
<td>Russia</td>
<td>Pressure buildup led to an explosive mechanical failure</td>
</tr>
<tr>
<td>1993</td>
<td>Cadarache</td>
<td>2</td>
<td>France</td>
<td>Spread of contamination to an area not expected by design</td>
</tr>
<tr>
<td>1989</td>
<td>Vandelloso</td>
<td>3</td>
<td>Spain</td>
<td>Near accident caused by fire resulting in loss of safety systems at the nuclear power station</td>
</tr>
<tr>
<td>1989</td>
<td>Greifswald</td>
<td></td>
<td>Germany</td>
<td>Excessive heating which damaged ten fuel rods</td>
</tr>
<tr>
<td>1986</td>
<td>Chernobyl</td>
<td>7</td>
<td>Ukraine (USSR)</td>
<td>Widespread health and environmental effects.</td>
</tr>
<tr>
<td>1986</td>
<td>Hamm-Uentrop</td>
<td></td>
<td>Germany</td>
<td>Spherical fuel pebble became lodged in the pipe used to deliver fuel elements to the reactor</td>
</tr>
<tr>
<td>1981</td>
<td>Tsuraga</td>
<td>2</td>
<td>Japan</td>
<td>More than 100 workers were exposed to doses of up to 155 millirem per day radiation</td>
</tr>
<tr>
<td>1980</td>
<td>Saint Laurent des Eaux</td>
<td>4</td>
<td>France</td>
<td>Melting of one channel of fuel in the reactor with no release outside the site</td>
</tr>
<tr>
<td>1979</td>
<td>Three Mile Island</td>
<td>5</td>
<td>US</td>
<td>Severe damage to the reactor core</td>
</tr>
<tr>
<td>1977</td>
<td>Bohunice</td>
<td>4</td>
<td>Czechoslovakia</td>
<td>Damage of fuel cladding and release of radioactivity</td>
</tr>
<tr>
<td>1969</td>
<td>Lucens</td>
<td></td>
<td>Switzerland</td>
<td>Total loss of coolant led to a power excursion and explosion of experimental reactor</td>
</tr>
<tr>
<td>1967</td>
<td>Chapelcross</td>
<td></td>
<td>UK</td>
<td>Graphite debris partially blocked a fuel channel causing a fuel element to melt and catch fire</td>
</tr>
<tr>
<td>1966</td>
<td>Monroe</td>
<td></td>
<td>US</td>
<td>Sodium cooling system malfunction</td>
</tr>
<tr>
<td>1964</td>
<td>Charlestown</td>
<td></td>
<td>US</td>
<td>Error by a worker at a United Nuclear</td>
</tr>
</tbody>
</table>
### power station accidents and incidents

<table>
<thead>
<tr>
<th>Year</th>
<th>Incident</th>
<th>INES level</th>
<th>Country</th>
<th>IAEA description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1959</td>
<td>Santa Susana Field Laboratory</td>
<td>US</td>
<td></td>
<td>Corporation fuel facility led to an accidental criticality</td>
</tr>
<tr>
<td>1958</td>
<td>Chalk River</td>
<td>Canada</td>
<td></td>
<td>Partial core meltdown</td>
</tr>
<tr>
<td>1958</td>
<td>Vinča</td>
<td>Yugoslavia</td>
<td></td>
<td>Due to inadequate cooling a damaged uranium fuel rod caught fire and was torn in two During a subcritical counting experiment a power buildup went undetected - six scientists received high doses</td>
</tr>
<tr>
<td>1957</td>
<td>Kyshtym</td>
<td>6</td>
<td>Russia</td>
<td>Significant release of radioactive material to the environment from explosion of a high activity waste tank.</td>
</tr>
<tr>
<td>1957</td>
<td>Windscale Pile</td>
<td>5</td>
<td>UK</td>
<td>Release of radioactive material to the environment following a fire in a reactor core A reactor shutoff rod failure, combined with several operator errors, led to a major power excursion of more than double the reactor's rated output at AECL's NRX reactor</td>
</tr>
<tr>
<td>1952</td>
<td>Chalk River</td>
<td>5</td>
<td>Canada</td>
<td></td>
</tr>
</tbody>
</table>

### INES Scale

<table>
<thead>
<tr>
<th>Level</th>
<th>Definition</th>
<th>People and environment</th>
<th>Radiological barriers &amp; control</th>
<th>Defence in depth</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Major accident</td>
<td>Major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures</td>
<td></td>
<td></td>
<td>Chernobyl, Ukraine, 1986</td>
</tr>
<tr>
<td>6</td>
<td>Serious accident</td>
<td>Likely to require implementation of planned countermeasures.</td>
<td></td>
<td></td>
<td>Kyshtym, Russia, 1957</td>
</tr>
<tr>
<td>5</td>
<td>Accident with Limited release of</td>
<td>- Severe damage</td>
<td></td>
<td></td>
<td>Windscale, UK,</td>
</tr>
<tr>
<td>Level</td>
<td>Definition</td>
<td>People and environment</td>
<td>Radiological barriers &amp; control</td>
<td>Defence in depth</td>
<td>Example</td>
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<td>-----------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>----------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>4</td>
<td>Accident with local consequences</td>
<td>radioactive material likely to require implementation of some planned countermeasures • Several deaths from radiation</td>
<td>• Minor release of radioactive material unlikely to result in implementation of planned countermeasures other than local food controls.</td>
<td>• Fuel melt or damage to fuel resulting in more than 0.1% release of core inventory.</td>
<td>FUKUSHIMA 1, 2011</td>
</tr>
<tr>
<td>3</td>
<td>Serious incident</td>
<td>• Exposure in excess of ten times the statutory annual limit for workers. • Non-lethal deterministic health effect (e.g., burns) from radiation.</td>
<td>• Release of significant quantities of radioactive material within an installation with a high probability of significant public exposure. • Exposure rates of more than 1 Sv/h in an operating area. • Severe contamination in an area not expected by</td>
<td>• Near accident at a nuclear power plant with no safety provisions remaining.</td>
<td>Sellafield, UK, 2005</td>
</tr>
<tr>
<td>Level</td>
<td>Definition</td>
<td>People and environment</td>
<td>Radiological barriers &amp; control</td>
<td>Defence in depth</td>
<td>Example</td>
</tr>
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<td>-------</td>
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<td>--------------------------------</td>
<td>-----------------</td>
<td>---------</td>
</tr>
<tr>
<td>1</td>
<td>Anomaly</td>
<td>• Overexposure of a member of the public in excess of statutory annual limits.</td>
<td>• Overexposure of a member of the public in excess of statutory annual limits.</td>
<td>• Minor problems with</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Incident</td>
<td>• Exposure of a member of the public in excess of 10 mSv. • Exposure of a worker in excess of the statutory annual limits.</td>
<td>• Radiation levels in an operating area of more than 50 mSv/h. • Significant contamination within the facility into an area not expected by design</td>
<td>• Significant failures in safety provisions but with no actual consequences. • Found highly radioactive sealed source, device or transport package with safety provisions intact. • Inadequate packaging of a highly radioactive sealed source.</td>
<td>Atucha, Argentina, 2005</td>
</tr>
</tbody>
</table>

- Low probability of significant public exposure.
- Lost or stolen highly radioactive sealed source.
- Misdelivered highly radioactive sealed source without adequate procedures in place to handle it.
<table>
<thead>
<tr>
<th>Level</th>
<th>Definition</th>
<th>People and environment</th>
<th>Radiological barriers &amp; control</th>
<th>Defence in depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>safety components with significant defence-in-depth remaining.</td>
<td></td>
</tr>
</tbody>
</table>
Appendix E4: Ecocentric Blog  

Uncategorized  

Nuclear Safety: U.S. ‘Near-Misses’ in 2010  

By Eben Harrell March 17, 2011Add a Comment  

There is a very important report out today by the Union of Concerned Scientists (UCS) on the performance of the Nuclear Regulatory Commission (NRC)—the government agency that enforces safety regulations for U.S. nuclear reactors in the hope of preventing a catastrophe such as is occurring in Fukushima. The report looks at 14 “near-misses” at U.S. nuclear plants during 2010. A summary of the findings can be found here, but the gist is that nuclear power plant operators in many cases may have shirked their safety responsibilities. “That plant owners could have avoided nearly all 14 near-misses in 2010 had they corrected known deficiencies in a timely manner suggests that our luck at nuclear roulette may someday run out,” the report concludes. The UCS report, titled “The NRC and Nuclear Power Plant Safety in 2010: A Brighter Spotlight Needed,” praises the NRC for what it calls a few “outstanding catches,” but also criticizes the NRC for, in several instances, not pushing plant operators hard enough to fix safety problems. (Update: For a statement from the NRC, see the bottom of this post).  

First, a note on how the reactor oversight process works in the U.S.: When an event occurs at a reactor, or when NRC inspectors discover damage or degraded equipment, the NRC undertakes a review of the risk to the reactor. The NRC undertook 200 such reviews in 2010, the UCS report states. When an event or condition increases the chance of reactor core damage by a factor of 10, then the NRC sends out a “Special Inspection Team” (SIT). When the risk rises by 100, the agency dispatches an “Augmented Inspection Team”. And when the risk increases by 1000 or more, the NRC sends out an “Incident Inspection Team.” The 14 near-misses in the UCS report are all the events that spurred the NRC to send out an SIT or an AIT. There was only one AIT—a series of problems at HB Robinson plant in South Carolina. About that incident, which involved a cooling system failure going unnoticed for 30 minutes, the UCS writes, “On the 31st anniversary of Three Mile Island, this event revisited nearly all the problems that caused that meltdown: bad design, poor maintenance, inadequate operator performance and poor training.”  

(PHOTOS: Inside the Fukushima Exclusion Zone)
Here is a brief summary of those near misses, taken from the report:

1) **Arkansas Nuclear One; Russellville, Arkansas; Operator: Entergy.** An SIT incident, no details publicly available because it was a security-related incident, and the NRC withholds such information in the wake of 9/11.

2) **Braidwood; Joilet, Illinois; Operator: Exelon.** An SIT incident, problems included floods in buildings with safety equipment, a poor design that allowed steam to rip metal siding off containment walls, and undersized electrical fuses for vital safety equipment.

3) **Brunswick; Southport, North Carolina; Operator: Progress Energy.** An SIT incident, equipment failure led the plant owner to declare an emergency. However, workers did not know how to operate the computer systems that notified offsite workers to report to emergency response facilities; staffing of these facilities took longer than required.

4) **Calvert Cliffs; Annapolis, Maryland; Operator: Constellation Energy.** An SIT incident, a roof known to leak for years, but ignored by the plant operator, shorts out electrical equipment; a reactor automatically shuts down. A warn-out protective device that workers had not replaced allows the electrical problem to trigger an automatic shut down of a second reactor.

5) **Catawba; Rock Hill; South Carolina; Operator: Duke Energy.** An SIT incident, no details publicly available. Another security-related incident.

6) **Crystal River 3; Crystal River, Florida; Operator: Progress Energy.** An SIT incident, workers inadvertently damage thick concrete reactor containment walls when cutting a hole to replace steam generators.

7) **David Besse; Toledo, Ohio; Operator: FirstEnergy.** An SIT incident, workers discover through-wall cracks in nozzles of “control rod drive mechanisms”–these cracks leak after workers fail to account for peak temperatures inside the reactor vessel.

8) **Diablo Canyon; San Luis Obispo, California; Operator: Pacific Gas & Electric.** An SIT incident, a misguided repair to valves that would not open fast enough prevent other key valves from working; the reactor operated for nearly 18 months with vital systems disabled.

9) **Farley; Sotham, Alabama; Operator: Southern Nuclear.** An SIT incident, a replacement pump with a manufacturing defect fails after workers did not ensure that it met key parameters specified in the purchase order.

10) **Fort Calhoun; Omaha, Nebraska; Operator: Omaha Public Power District.** An SIT incident, pumps in an emergency water system fail repeatedly over several years.

11) **HB Robinson; Florence, South Carolina; Operator: Progress Energy.** An AIT incident. An electrical cable shorts out and starts a fire. Electrical problems disrupt the supply of cooling water to the pump seals for the reactor coolant system; cooling water leaks into the
containment building. Control room operators do not notice the lack of cooling for more than 30 minutes. The reactor shuts down, and the operator starts two pumps that transfer water from a tank in an auxiliary building. When the tank empties, the pumps are supposed to automatically realign to take water from another storage tank. The realignment fails to happen, and operators do not notice the failure for nearly an hour. Four hours into the event, the operators attempt to restore power, but do not check first to ensure that workers had fixed the original fault. When the operators close the electrical breaker to a circuit, they cause another short out, and another fire.

12) **HB Robinson; Florence, South Carolina; Operator: Progress Energy.** An SIT incident, one of four pumps supplying cooling water to the reactor vessel experiences motor failure and automatically shuts down. A series of operator errors trying to compensate for the problem ensues.

13) **Surry; Newport News, Virginia; Operator: Dominion Generation.** An SIT incident, after an inadvertent shutdown of a reactor, a fire starts in the control room due to an overheated electrical component. A similar component in another unit’s control room had started a fire six months earlier, but the operator failed to fix the problem in other control rooms.

14) **Wolf Creek; Burlington, Kansas; Operator: Wolf Creek Nuclear.** An SIT. The UCS report finds: “Seven hours after the reactor shut down automatically because of a problem with the electrical grid, an NRC inspector found water leaking from the system that cools the emergency diesel generators and virtually all other emergency equipment. An internal study in 2007 had forecast such leakage, and a leak had actually occurred after a reactor shutdown in April 2008. However, the owner had taken few steps to correct this serious safety problem.” The USC report goes on to list a few “outstanding catches” made by the NRC’s inspection teams. For example, commission inspectors refused to accept the decision of supervisors at South Carolina’s Oconee plant not to inspect safety systems on the facility’s Units 2 and 3 after failure of the safety system on Oconee’s Unit 1. According to the report, “NRC inspectors persistently challenged lame excuse after lame excuse until the company finally agreed to test the other two units. When it did so, their systems failed, and NRC inspectors ensured that the company corrected the problems.” Another catch came at the Browns Ferry Plant in Arkansas, when inspectors found that an oil leak could cause a coolant injection system to fail in an emergency. And yet another occurred at Kawaunee nuclear plant in Wisconsin, when NRC inspectors found that workers were inadvertently disabling a safety system during routing testing operations that occurred while the reactor was still running.

*(PHOTOS: The Worst Nuclear Disasters)*
But the USC report also said that “the NRC did not always serve the public well in 2010.” It lists three safety breaches from Peach Bottom (Pennsylvania), Indian Point (New York), and Vermont Yankee (Vermont) power plants that it says the NRC overlooked or dismissed. The report states that “At Indian Point, the NRC discovered that the liner of a refueling cavity at Unit 2 has been leaking since at least 1993. By allowing this reactor to continue operating with equipment that cannot perform its only safety function, the NRC is putting people living around Indian Point at elevated and undue risk.”

At Peach Bottom, the report claims, the NRC allowed the plant operator to run a reactor with control rods that do not work quickly enough—the rods are designed to quickly shut down a nuclear reaction and thus their failure could prompt a run-away nuclear chain reaction as occurred at Chernobyl.

And at Vermont Yankee, the report says that the NRC allowed the plant operator to continue operating even though it had detected radioactively contaminated water in an on site monitoring well.

The UCS report concludes, “Because we have not reviewed all NRC actions, the three positive and three negative examples do not represent the agency’s best and worst performances in 2010. Instead, the examples highlight patterns of NRC behavior that contributed to these outcomes. The positive examples clearly show that the NRC can be an effective regulator. The negative examples attest that the agency still has work to do to become the regulator of nuclear power that the public deserves.”

**Update:** The NRC sent me the following statement on March 18: “We have not yet had a chance to review the latest report from the Union of Concerned Scientists. However, we can say that the NRC’s current Reactor Oversight Process has been in place since April 2000 and has worked effectively to gauge the performance of U.S. nuclear power plants. It does so through a combination of Performance Indicators, such as the number of unplanned shutdowns, and NRC inspection findings. If the NRC observes any indications of declining performance, the agency can ratchet up its oversight to ensure issues are being addressed in a timely manner. The NRC does not hesitate to increase its level of scrutiny wherever and whenever that is warranted.”

Appendix F1: Assessment of Impact (Dale Academy)

Name: __________________________
Date: __________________________

Applying Statistical Knowledge: Safety of nuclear power plants

Goal: Determining which source of energy is safer: coal or nuclear
Based on the empirical data, you were asked to determine the probability of a nuclear accident. The consensus between groups was that the probability of an accident was small.

1. In determining the risk of a nuclear accident do we have to consider anything else besides probability? Please discuss.

2. Here is a quote from one of your peers from a pre-test about safety of nuclear power plants:

““you don’t know how drastic a nuclear accident is to another power plant accident (of a different form) ….. There may be few nuclear accidents , but they may be much more devastating than lots of other power plant accidents.”

Do you agree with the statement?

3. Experts determining environmental, financial or any other kind of risk agree with the above statement. They say that besides probability of an event we have to look at its impact.

What data could we use to determine the impact of an accident?

You will try to determine whether the risk of an accident is higher for coal power plants or nuclear power plants.
The following data was obtained from the Organization for Economic Cooperation and Development (OECD) report. It gives a breakdown of accidents in power plants that resulted in more than 5 immediate fatalities (deaths). This data is up to year 2000.

<table>
<thead>
<tr>
<th>Energy Chain</th>
<th>Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1119</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1</td>
</tr>
</tbody>
</table>

4. According to this data, the working definition of impact is “number of accidents resulting in more than 5 immediate fatalities”
Do you agree with this working definition? Why or why not?

5. We could compare accidents for coal and nuclear power plants to determine which accident has a bigger impact. Here is information on the number of (immediate) deaths in these accidents:

<table>
<thead>
<tr>
<th>Energy Chain</th>
<th>Accidents</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1119</td>
<td>20276</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1</td>
<td>31</td>
</tr>
</tbody>
</table>

Based on this data, determine which one has a smaller impact.
________________________ has a greater impact. The impact is ____________ times greater than ________________.

6. Is there anything else we need to consider when talking about impact? Based on your knowledge, intuition, beliefs, or other data, how does the impact of coal compare to nuclear power plants (need a numerical answer).

7. Based on both impact and probability, we can try to determine the risk of accident for each source of energy.

Please copy your data for probability and impact in the table (for the simplicity case, I estimated that the probability of a coal accident is 10 times more than nuclear):
8. How could we combine the data on probability and impact to arrive at the overall risk?

9. Based on your answer to 8, how does the risk of a nuclear power plant accident compare to the risk of coal power plant accident?

10. How did your beliefs influence your answer? Is it possible to get an answer without considering one’s beliefs and biases? Why or why not?
Appendix F2: Assessment of Impact (St Hubertus Secondary School)

Name: __________________________
Date: __________________________

Applying Statistical Knowledge: Safety of nuclear power plants

Goal: Determining which source of energy is safer: coal or nuclear

Yesterday, based on the empirical data, you were asked to determine the probability of a nuclear accident.

1. In determining the risk of a nuclear accident do we have to consider anything else besides probability? Please discuss.

2. Experts determining environmental, financial or any other kind of risk believe that besides the probability of an event we have to look at its impact.

What data could we use to determine the impact of an accident?

RISK ASSESSMENT

You will try to determine whether the risk of an accident is higher for coal power plants or nuclear power plants.

The following data was obtained from the Organization for Economic Cooperation and Development (OECD) report. It gives a breakdown of accidents in power plants that resulted in more than 5 immediate fatalities (deaths). This data is up to year 2000.

<table>
<thead>
<tr>
<th>Energy Chain</th>
<th>Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1119</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1</td>
</tr>
</tbody>
</table>

4. According to this data, the working definition of impact is “number of accidents resulting in more than 5 immediate fatalities”
Do you agree with this working definition? Why or why not?
5. We could compare accidents for coal and nuclear power plants to determine which accident has a bigger impact. Here is information on the number of (immediate) deaths in these accidents:

<table>
<thead>
<tr>
<th>Energy Chain</th>
<th>Accidents</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1119</td>
<td>20276</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1</td>
<td>31</td>
</tr>
</tbody>
</table>

Based on this data, determine which one has a smaller impact.

___________________ has a greater impact. The impact is ______________ times greater than ___________________.

6. Is there anything else we need to consider when talking about impact? Based on your knowledge, intuition, beliefs, or other data, how does the impact of coal compare to nuclear power plants (need a numerical answer).

7. Based on both impact and probability, we can try to determine the risk of accident for each source of energy.

Please copy your data for probability and impact in the table (for the simplicity case, I estimated that the probability of a coal accident is 10 times more than nuclear):

<table>
<thead>
<tr>
<th></th>
<th>Probability</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>10x(nuclear)=</td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One way to assess the risk is to use Risk Impact vs. Probability Graph (Fig 1).

Plot the impact vs. probability using the data you obtained for the coal and for the nuclear power plants. Compare them.
8. How could we combine the data on probability and impact to arrive at the overall risk?

9. Based on your answer to 8, how does the risk of a nuclear power plant accident compare to the risk of coal power plant accident.
Appendix G1: Assent Form to Participate in the Research

Dear ___________,

I am writing in order to request for permission to participate in educational research at your school as a part of my PhD dissertation work. I am a third year PhD student at the Ontario Institute for Studies in Education of the University of Toronto (OISE/UT).

In my PhD research, I have been looking into students’ understanding of risk as well as exploring ways of fostering their understanding of risk. Risk is an important concept with applications in many areas including engineering, medicine, law and economics. Research has shown that most of the students as well as adults have problems with interpreting data involving risk. This is why there is a need for additional research in this area.

My plan is to use a design research methodology which involves my working with teacher developing lesson plans for the IB1 probability unit as well as working with the students for the duration of the unit. My goal is to improve students' understanding of probability concepts but also to gain insight into students' probabilistic thinking and reasoning which is connected to the understanding of risk. The research would happen in the period of April of 2011 to June of 2012. In April of 2011, I am planning to meet with the teachers to plan for the design experiment which will take place during the IB1 probability unit.

I would also like to assure you that the identity of the school, the teachers and students will be protected. I believe my research will give the teachers the opportunity to gain more insight into the students’ learning. The lesson plans or any other teaching methods or material would be available for the future use by the school if so desired. Should you agree to approve my study, please sign both copies of the attached consent form and keep one for your records.

For questions about your rights as a research participant contact the Office of the Research Ethics from the University of Toronto, at 12 Queen’s Park Cres. West, McMurrich Building, 3rd Floor, Toronto, ON M5S 1S8, phone 416-946-3273, fax 416-946-5763 or email: ethicsreview@utoronto.ca

Thank you in advance for assistance and cooperation.

Thank you for your time. I am looking forward to hearing from you.

Sincerely yours,

Nenad Radakovic
CONTACT INFORMATION:

**Principal Investigator:** Nenad Radakovic

**Supervisor:** Dr. Douglas McDougall, Associate Professor

Department of Curriculum, Teaching & Learning
Ontario Institute for Studies in Education/UT,
252 Bloor Str. W., Toronto, ON, M5S1V6

Room 11-239A
Tel: XXX
E-mail: XXX

Room 11-250
Tel: XXX
E-mail: XXX
Appendix G2: Parental Consent Form to Participate in the Research

Dear ___________.

I am writing in order to request for permission for your child to participate in educational research at his/her school as a part of my PhD dissertation work. I am a third year PhD student at the Ontario Institute for Studies in Education of the University of Toronto (OISE/UT).

In my PhD research, I have been looking into students’ understanding of risk as well as exploring ways of fostering their understanding of risk. Risk is an important concept with applications in many areas including engineering, medicine, law and economics. Research has shown that most of the students as well as adults have problems with interpreting data involving risk. This is why there is a need for additional research in this area.

My plan is to use a design research methodology which involves my working with the teacher on developing lesson plans for the IB1 probability unit as well as working with the students for the duration of the unit. My goal is to improve students' understanding of probability concepts but also to gain insight into students' probabilistic thinking and reasoning which is connected to the understanding of risk. The research would happen in the period of April of 2011 to June of 2012. In April of 2011, I am planning to meet with the teachers to plan for the design experiment which will take place during the IB1 probability unit.

I would also like to assure you that the identity of the school, the teachers and students will be protected. I believe my research will give the teachers the opportunity to gain more insight into the students’ learning. The lesson plans or any other teaching methods or material would be available for the future use by the school if so desired. Should you agree to approve my study, please sign both copies of the attached consent form and keep one for your records.

For questions about your rights as a research participant contact the Office of the Research Ethics from the University of Toronto, at 12 Queen’s Park Cres. West, McMurrich Building, 3rd Floor, Toronto, ON M5S 1S8, phone 416-946-3273, fax 416-946-5763 or email: ethicsreview@utoronto.ca

Thank you in advance for assistance and cooperation.

Thank you for your time. I am looking forward to hearing from you.

Sincerely yours,

Nenad Radakovic
<table>
<thead>
<tr>
<th>CONTACT INFORMATION:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principal Investigator:</strong></td>
</tr>
<tr>
<td>Nenad Radakovic</td>
</tr>
<tr>
<td><strong>Supervisor:</strong></td>
</tr>
<tr>
<td>Dr. Douglas McDougall, Associate Professor</td>
</tr>
<tr>
<td>Department of Curriculum, Teaching &amp; Learning</td>
</tr>
<tr>
<td>Ontario Institute for Studies in Education/UT,</td>
</tr>
<tr>
<td>252 Bloor Str. W., Toronto, ON, M5S1V6</td>
</tr>
<tr>
<td>Room 11-239A</td>
</tr>
<tr>
<td>Tel: XXX</td>
</tr>
<tr>
<td>E-mail: XXX</td>
</tr>
<tr>
<td>Room 11-250</td>
</tr>
<tr>
<td>Tel: XXX</td>
</tr>
<tr>
<td>E-mail: XXX</td>
</tr>
</tbody>
</table>
Appendix G3: Teacher Consent Form to Participate in the Research

Dear __________,

I am writing in order to request for permission to participate educational research at your school as a part of my PhD dissertation work. I am a third year PhD student at the Ontario Institute for Studies in Education of the University of Toronto (OISE/UT).

In my PhD research, I have been looking into students’ understanding of risk as well as exploring ways of fostering their understanding of risk. Risk is an important concept with applications in many areas including engineering, medicine, law and economics. Research has shown that most of the students as well as adults have problems with interpreting data involving risk. This is why there is a need for additional research in this area.

My plan is to use a design research methodology which involves my working with you on developing lesson plans for the IB1 probability unit as well as working with the students for the duration of the unit. My goal is to improve students' understanding of probability concepts but also to gain insight into students' probabilistic thinking and reasoning which is connected to the understanding of risk. The research would happen in the period of April of 2011 to June of 2012. In April of 2011, I am planning to meet with the teachers to plan for the design experiment which will take place during the IB1 probability unit.

I would also like to assure you that the identity of the school, the teachers and students will be protected. I believe my research will give the teachers the opportunity to gain more insight into the students’ learning. The lesson plans or any other teaching methods or material would be available for the future use by the school if so desired. Should you agree to approve my study, please sign both copies of the attached consent form and keep one for your records.

For questions about your rights as a research participant contact the Office of the Research Ethics from the University of Toronto, at 12 Queen’s Park Cres. West, McMurrich Building, 3rd Floor, Toronto, ON M5S 1S8, phone 416-946-3273, fax 416-946-5763 or email: ethicsreview@utoronto.ca

Thank you in advance for assistance and cooperation.

Thank you for your time. I am looking forward to hearing from you.

Sincerely yours,

Nenad Radakovic
**CONTACT INFORMATION:**

*Principal Investigator:* Nenad Radakovic  
*Supervisor:* Dr. Douglas McDougall, Associate Professor  

Department of Curriculum, Teaching & Learning  
Ontario Institute for Studies in Education/UT,  
252 Bloor Str. W., Toronto, ON, M5S1V6

<table>
<thead>
<tr>
<th>Room 11-239A</th>
<th>Room 11-250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tel: XXX</td>
<td>Tel: XXX</td>
</tr>
<tr>
<td>E-mail: XXX</td>
<td>E-mail: XXX</td>
</tr>
</tbody>
</table>

---

**Researcher Signature**  
**Date**

**Participant Signature**  
**Date**
### Appendix H: Dale Academy Students’ Arguments about Impact from the Initial Assessment

<table>
<thead>
<tr>
<th>Student</th>
<th>Agree with the statement?</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luis</td>
<td>No</td>
<td>“What if one failure at a nuclear power plant destroyed the world?”</td>
</tr>
<tr>
<td>Samir</td>
<td>No</td>
<td>“Ramifications are much more severe.”</td>
</tr>
<tr>
<td>Luca</td>
<td>No</td>
<td>&quot;Big deal when the accident happens.&quot; &quot;We have to factor in the danger when the accident happens.&quot;</td>
</tr>
<tr>
<td>Andrew</td>
<td>No</td>
<td>“Don't know how drastic a nuclear accident is to another power plant accident.&quot; “They may be much more devastating.”</td>
</tr>
<tr>
<td>Federico</td>
<td>No</td>
<td>“Depends on the scale of power plant accident.”</td>
</tr>
<tr>
<td>Mario</td>
<td>No</td>
<td>“Nuclear power is very dangerous.”</td>
</tr>
<tr>
<td>Adam</td>
<td>Yes</td>
<td>“The dangers of coal to the environment are far worse than the dangers of nuclear energy.”</td>
</tr>
<tr>
<td>Clint</td>
<td>No</td>
<td>“It depends on the extent of the damage.”</td>
</tr>
</tbody>
</table>
Appendix I: Dale Academy Students’ Background Knowledge about Fukushima Accident Compared to Their Views on Safety of Nuclear Power Plants

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Blair</td>
<td>2</td>
<td>Depends on the context</td>
<td>No</td>
<td>No</td>
<td>“Assessment of safety should be done on a case to case basis.”</td>
</tr>
<tr>
<td>Jared</td>
<td>2</td>
<td>Yes with a qualifier</td>
<td>Yes</td>
<td>Yes</td>
<td>Impact: “when it happens, dangerous.” Likelihood: “probability low.”</td>
</tr>
<tr>
<td>Luis</td>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Aaron</td>
<td>2.5</td>
<td>Yes with a qualifier</td>
<td>No</td>
<td>No</td>
<td>“Nuclear plants need to spend more money on preventing catastrophes from happening again.”</td>
</tr>
<tr>
<td>David</td>
<td>2</td>
<td>Yes</td>
<td>yes</td>
<td>Yes</td>
<td>Impact: &quot;minimal number of people died.&quot; Likelihood: &quot;there have been only three major incidents.&quot;</td>
</tr>
<tr>
<td>Samir</td>
<td>2.5</td>
<td>Yes with qualifier</td>
<td>No</td>
<td>No</td>
<td>“They are safe in the stable areas, but Japan is right on multiple plate areas, bad call.”</td>
</tr>
<tr>
<td>Cai</td>
<td>2.5</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Impact: “5000 workers are killed each year mining in coal plants.”</td>
</tr>
<tr>
<td>Marco</td>
<td>2.5</td>
<td>Yes, with a qualifier</td>
<td>No</td>
<td>No</td>
<td>“Through the incident, I have doubts now on the safety measures taken to ensure that nuclear power plants are not prone to damage from environmental disaster.” He was in Hong Kong during the accident.</td>
</tr>
<tr>
<td>Anjun</td>
<td>2</td>
<td>Yes, with qualifier</td>
<td>No</td>
<td>No</td>
<td>Not concerned about disasters, but concerned about waste and radiation.</td>
</tr>
<tr>
<td>Name</td>
<td>Rating</td>
<td>Agreement</td>
<td>Qualifier</td>
<td>Impact</td>
<td>Likelihood</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>------------</td>
<td>-----------</td>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>Luca</td>
<td>2.5</td>
<td>Yes</td>
<td>with</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Andrew</td>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Zu-Zhang</td>
<td>2</td>
<td>Yes</td>
<td>with a</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Federico</td>
<td>3</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Adam</td>
<td>2</td>
<td>Yes</td>
<td>with a</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Alex</td>
<td>2.5</td>
<td>Yes</td>
<td>with a</td>
<td>Yes</td>
<td>yes</td>
</tr>
<tr>
<td>Jordan</td>
<td>2.5</td>
<td>Yes</td>
<td>with a</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Nathan</td>
<td>0.5</td>
<td>Not</td>
<td>specifically</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Fahad</td>
<td>2.5</td>
<td>Yes</td>
<td>with a</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Robert</td>
<td>3</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Clint</td>
<td>2</td>
<td>Yes</td>
<td>with a</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Mean 2.23
St. Dev. 0.51
# Appendix J: Dale Academy Students’ Choice of Data Source

<table>
<thead>
<tr>
<th>Group (Students)</th>
<th>Most reliable website</th>
<th>Reason(s) for choosing the website</th>
<th>Reason(s) for least reliable website</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>David, Fahad, Samir, Sasha</td>
<td>The Guardian</td>
<td>“Not the stakeholder on the issue.”</td>
<td>The Guardian</td>
<td>Reliability</td>
</tr>
<tr>
<td>Blair, Robert, Federico, Cai</td>
<td>The World Nuclear Association</td>
<td>“It’s an organization measuring those things.”</td>
<td>The World Nuclear Association</td>
<td>“It would probably have a good estimate of what’s going on.”</td>
</tr>
<tr>
<td>Luis, Jared, Luca, Clint</td>
<td>The Guardian, Green Peace, and World Nuclear</td>
<td>Either .org or .uk.</td>
<td>The Guardian</td>
<td>Presentation of data: severity presented in terms of colour and value. Clear and concise.</td>
</tr>
<tr>
<td>Adam, Andrew, Zu-Zhang, Mario</td>
<td>The Guardian</td>
<td>“Uses and cites primary sources.” “Generally known to be trustworthy.”</td>
<td>The Guardian</td>
<td>“Depth of resources.” “The Guardian is a reliable newspaper.” Presentation of data: it classified the accidents according to severity. “More than one source.”</td>
</tr>
<tr>
<td>Jordan, Alex, Aaron</td>
<td>World Nuclear Association</td>
<td>“It is the source that records the actual data.”</td>
<td>The Guardian</td>
<td>Presentation of Data: severity described by the colour.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Green Peace</td>
</tr>
<tr>
<td>Nathan, Lee, Anjun, Marco</td>
<td>Guardian</td>
<td>“It’s held accountable.”</td>
<td>The Guardian</td>
<td>“Most comprehensible.” Presentation of data: Detailed explanation of each incident with the effect on the environment “Presents data in a professional manner and effectively.”</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------</td>
<td>--------------------------</td>
<td>--------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Green Peace</td>
<td>“Exaggerating claims to make nuclear energy seem dangerous.”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It provides summary.
Appendix K: Dale Academy Students’ Findings for the Nuclear 2 Activity

<table>
<thead>
<tr>
<th>Group</th>
<th>Factors impacting risk</th>
<th>Assessment of impact</th>
<th>Coordination between probability and impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>David, Samir, Sasha, and Fahad</td>
<td>“Demographics; socio-economic status; community preparedness; ability to respond; safety standards of plant; hand eye coordination.”</td>
<td>“Coal 654 times greater than nuclear.”</td>
<td>Answers only based on likelihood. Likelihood of nuclear = 0.025</td>
</tr>
<tr>
<td>Luis, Jared, Luca, and Clint</td>
<td>“The environment around the nuclear power; plant/ location/ plate boundaries, the time of the year/ predicted weather patterns.”</td>
<td>“Coal 654 times Greater than nuclear.”</td>
<td>Likelihood = 0.013 “Impact for coal is big. Impact for nuclear is astronomical.” “You can multiply them to obtain the product.” Risk of accident: Nuclear Power Plant &gt; Coal Power Plant</td>
</tr>
<tr>
<td>Adam, Andrew, Zu-Zhang, and Mario</td>
<td>“Safety protocol.” “Number of people working in plant.”</td>
<td>“Nuclear has a greater impact because it is approximately 2 times deadlier.”</td>
<td>Likelihood = 0.0746 Impact for Coal = 18.11 Impact for Nuclear = 31 Impact x Probability = Risk 31 x 0.0746 = 2.3 18.11 x 0.746 = 13.5 Risk for coal is much higher</td>
</tr>
<tr>
<td>Jordan, Alex, Aaron, and Ray</td>
<td>“Demographics, socio-economic, preparedness before event, response after the event.” “Social, economic, political systems.”</td>
<td>“Nuclear has greater impact. The impact is 1.5X greater than coal.”</td>
<td>Likelihood for coal = 0.0042 Impact for coal = 1.0 x 100 Impact for nuclear 0.00042 Impact for coal = 1.5 x 100 Overall risk of coal = 0.42 Overall risk of nuclear: 0.063 Risk = Probability x</td>
</tr>
</tbody>
</table>
Nathan, Lee, Anjun, and Marco

“The effect of an accident.”

“Coal has a greater impact.”

“The impact is 654 times greater than nuclear.”

Impact

“Coal-powered plants have more risk.”

Risk = Probability x Impact
## Appendix L: St. Hubertus Students’ Arguments about Impact from the Initial Assessment

<table>
<thead>
<tr>
<th>Student</th>
<th>Agrees with the statement?</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloe</td>
<td>Yes with a qualifier</td>
<td>&quot;The effects of a nuclear power plants malfunction/accidents would classify them as dangerous in my opinion.&quot;</td>
</tr>
<tr>
<td>Priya</td>
<td>No</td>
<td>“Radiation causes so much harm to the body.” “The power plant in Japan caused a great deal of damage.”</td>
</tr>
<tr>
<td>Andy</td>
<td>Neither agrees nor disagrees</td>
<td>&quot;Water, wind, and sunlight sound safe while using radioactive materials are dangerous.&quot;</td>
</tr>
<tr>
<td>Anoush</td>
<td>No</td>
<td>&quot;Massive and dangerous&quot;; &quot;A life threatening item&quot;</td>
</tr>
<tr>
<td>Talia</td>
<td>No</td>
<td>“Dangerous and hard to handle”</td>
</tr>
<tr>
<td>Mina</td>
<td>No</td>
<td>“One accident causes problems for decades.”</td>
</tr>
<tr>
<td>Joseph</td>
<td>No</td>
<td>&quot;3 significant power plant accidents wiped out thousands of people within that area.” Nuclear powerplants &quot;devastating and not worth the risk.”</td>
</tr>
<tr>
<td>Pouneh</td>
<td>No, implicitly</td>
<td>&quot;3 significant accidents out of 500 is good, it is also bad at the same time. These accidents can kill many people which is a threat to the government.”</td>
</tr>
</tbody>
</table>
Appendix M: St Hubertus Students’ Background Knowledge about Fukushima Accident Compared to Their Views on Safety of Nuclear Power Plants

<table>
<thead>
<tr>
<th>Student name</th>
<th>PreQ2: level</th>
<th>PreQ2: Safe?</th>
<th>PreQ2: Impact?</th>
<th>PreQ2: Likelihood</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloe</td>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>“I don’t think the payoff is worth the risk of nuclear power plants. They are safer but on the occasion of failure the failure is too catastrophic. “</td>
</tr>
<tr>
<td>Emina</td>
<td>2</td>
<td>Not explicitly</td>
<td>No</td>
<td>No</td>
<td>Against</td>
</tr>
<tr>
<td>Sara</td>
<td>1.5</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Hiroko</td>
<td>2.5</td>
<td>Not explicitly</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Karl</td>
<td>1.5</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Larissa</td>
<td>0</td>
<td>“I don't know.”</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Maya</td>
<td>2</td>
<td>Not explicitly</td>
<td>Yes</td>
<td>No</td>
<td>“Enhance safety.”</td>
</tr>
<tr>
<td>Connie</td>
<td>1.5</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Priya</td>
<td>2.5</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Joao</td>
<td>2</td>
<td>Yes, with a qualifier</td>
<td></td>
<td></td>
<td>Qualifier: minimize harm, better location.</td>
</tr>
<tr>
<td>Andy</td>
<td>2.5</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>“The power plant was on a verge to destroy part of earth.”</td>
</tr>
<tr>
<td>Anoush</td>
<td>1.5</td>
<td>Not explicitly</td>
<td>No</td>
<td>No</td>
<td>“I think that nuclear power plants should increase their safety, especially after the Fukushima incident. All precautions possible should be taken. You can never be too safe.”</td>
</tr>
<tr>
<td>Name</td>
<td>Score</td>
<td>Support</td>
<td>Familiarity</td>
<td>Opinion</td>
<td>Reason</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>---------</td>
<td>-------------</td>
<td>---------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Talia</td>
<td>1</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Negative</td>
</tr>
<tr>
<td>Dale</td>
<td>1</td>
<td>Not explicitly</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Mina</td>
<td>0</td>
<td>I don't know</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Natasha</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>“Benefits outweigh risk.”</td>
</tr>
<tr>
<td>Amira</td>
<td>0.5</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td>&quot;More risk than benefits in terms of safety and health.&quot;</td>
</tr>
<tr>
<td>Lina</td>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>&quot;Can be very deadly.&quot;</td>
</tr>
<tr>
<td>Joseph</td>
<td>1.5</td>
<td>Yes, with a qualifier</td>
<td>Yes</td>
<td>No</td>
<td>“I think that nuclear energy is relatively safe and a great source of clean energy but with it also comes the risk of a devastating meltdown which can destroy a lot of land, property and most importantly people.”</td>
</tr>
<tr>
<td>Louvie</td>
<td>1.5</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>“I don’t know much about them but when I think of finding a place to live I definitely do not think of moving next to a nuclear power plant. I think that there is a higher chance of something going wrong when dealing with nuclear energy as opposed to, let’s say, electromagnetic energy or radiant energy. Also, the consequences of nuclear energy are more detrimental than the consequences of other forms of energy.”</td>
</tr>
<tr>
<td>Iris</td>
<td>1.5</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Helen</td>
<td>0</td>
<td>Not explicitly</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Pouneh</td>
<td>2.5</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>MEAN</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST. DEV</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Appendix N: St Hubertus Students’ Choice of Data Source

<table>
<thead>
<tr>
<th>Group</th>
<th>Most reliable</th>
<th>Reason</th>
<th>Website Chosen</th>
<th>Reason(s) for choosing the website</th>
<th>Least reliable website</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priya, Iris, Maya, and Joseph</td>
<td>The Guardian</td>
<td>Impartial</td>
<td>The Guardian</td>
<td>“Lists all major accidents.” “Provides the levels.”</td>
<td>World Nuclear Association</td>
<td></td>
</tr>
<tr>
<td>Lina, Andy, Louvie, Karl, Connie</td>
<td>The Guardian</td>
<td>Least biased</td>
<td>The Guardian</td>
<td>Reliability</td>
<td>World Nuclear Association</td>
<td>“Their perspective is very narrow and only focused on the nuclear power.”</td>
</tr>
<tr>
<td>Chloe, Mina, Larissa, Dana, and Sara</td>
<td>Green Peace</td>
<td>The Guardian</td>
<td>“List more comprehensive, organized, and easily understood.”</td>
<td>World Nuclear Association</td>
<td>“It has political and financial motives.”</td>
<td></td>
</tr>
</tbody>
</table>
# Appendix O: St Hubertus Students’ Findings for the Nuclear 2 Activity

<table>
<thead>
<tr>
<th>Group</th>
<th>Factors impacting risk</th>
<th>Assessment of impact</th>
<th>Coordination between likelihood and impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priya, Iris, Maya, and Joseph</td>
<td>“Degree of accident.”</td>
<td>Impact 1.72 higher for nuclear</td>
<td>Used both the product formula method and graphing method. Product: coal energy more risky. Graphing: nuclear more risky.</td>
</tr>
<tr>
<td>Connie, Joao, Karl, Andy, Lina, Louvie</td>
<td>“Type of material used. Location- how prone it is to disaster, how ‘technologically advanced it is.” “The age.”</td>
<td>“How many people hurt, how many people injured but not dead, environmental damage, financial, long term impact.” The impact of nuclear is 0.03 accidents/fatality, the impact for coal is 0.05 accidents/fatality which is interpreted to mean that the impact for nuclear was lower.</td>
<td>Not obtained, probability and impact seen as negatively correlated</td>
</tr>
<tr>
<td>Hiroko, Chloe, Dana, Mina, Larissa.</td>
<td>“Human, social, environmental impact and unforeseeable (uncontrollable) circumstances.”</td>
<td>Impact is any difference before and after the event. “Serious injuries, environmental devastation, dollars spent.” The impact for coal was 654 times higher</td>
<td>Used qualitative measure of impact to define</td>
</tr>
<tr>
<td>Hellen, Pouneh, Amira, Talia</td>
<td>Human error, safety</td>
<td>Numerical values: Impact 1.72 times higher for nuclear</td>
<td>Used numerical values for impact to locate it on the chart</td>
</tr>
<tr>
<td>Student</td>
<td>Safe?</td>
<td>Impact?</td>
<td>Comment</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Chloe</td>
<td>No</td>
<td>Yes</td>
<td>“The impact is much larger and more devastating than other forms of generating power.”</td>
</tr>
<tr>
<td>Karl</td>
<td>No</td>
<td>Yes- implicitly</td>
<td>&quot;It will kill many people and make the land infertile for years.&quot;</td>
</tr>
<tr>
<td>Connie</td>
<td>No</td>
<td>Yes</td>
<td>Mentioned immediate deaths from Chernobyl, long term consequences, spillage.</td>
</tr>
<tr>
<td>Priya</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joao</td>
<td>No</td>
<td>Yes</td>
<td>&quot;Nuclear accidents have an enormous impact.” &quot;We have to look at accidents and impact it had.”</td>
</tr>
<tr>
<td>Talia</td>
<td>No</td>
<td>Yes</td>
<td>&quot;Nuclear power plants have a very big impact but a less of a chance of occurring.&quot; “The effects not safe.”</td>
</tr>
<tr>
<td>Name</td>
<td>Vote</td>
<td>Impact</td>
<td>Statement</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>--------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Dana</td>
<td>No</td>
<td>Yes</td>
<td>&quot;Severity too high.&quot;</td>
</tr>
<tr>
<td>Mina</td>
<td>No</td>
<td>Yes, implicitly</td>
<td>&quot;The effects are severe.&quot;</td>
</tr>
<tr>
<td>Amira</td>
<td>No</td>
<td>Yes</td>
<td>&quot;It depends on definition of what impact is.&quot;</td>
</tr>
<tr>
<td>Joseph</td>
<td>No</td>
<td>Yes</td>
<td>Mentions impact implicitly, as &quot;risk.&quot;</td>
</tr>
<tr>
<td>Louvie</td>
<td>No</td>
<td>Yes</td>
<td>&quot;There may be a small amount of significant accidents, but the impact of these accidents are great.&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depends on whether you look at immediate deaths or long-term effects.</td>
</tr>
<tr>
<td>Iris</td>
<td>No</td>
<td>Yes</td>
<td>&quot;The impact of one accident is extremely dangerous&quot;. Affects people who live in the area and &quot;following&quot; generations.</td>
</tr>
<tr>
<td>Name</td>
<td>Response 1</td>
<td>Response 2</td>
<td>Comments</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Hellen</td>
<td>No</td>
<td>Yes</td>
<td>&quot;The accidents have a huge impact. Huge effects on future generations.&quot;</td>
</tr>
<tr>
<td>Pounch</td>
<td>No</td>
<td>Yes, implicitly</td>
<td>&quot;High risk of people dying&quot;</td>
</tr>
</tbody>
</table>
Appendix Q: Teacher Questions

Background questions
1. What is your name?
2. What courses are you currently teaching and what is your role in the school?
3. How long have you worked at this school?
4. Where did you teach before and what courses have you taught?
5. How many years have you been teaching?
6. Where did you go to university?
7. Why did you become a teacher?

1. Versions of success
   For you, what counts as success for students in this school?
   What are your goals for students in education?
   How widely accepted are your goals with other teachers in the department? The school? Among parents?

2. Student engagement
   How would you define student engagement?
   What can teachers do to increase student engagement?
   To what extent do you consider student engagement when planning your lessons?
   What components of student life do you believe are affected by low and/or high student engagement? How are they affected?

3. Challenging circumstances
   What are the most challenging things for you in this school as you go about your work?
   Do you think this school is different from other schools in its challenges?
   How would you describe the community of parents with whom you work?
   How has the school context changed over the past few years, and what changes are going on now?

4. Mathematics
   How would you describe your goals in mathematics?
   How widely accepted are these views in the department? At the school? Among the parents?

5. Probability and Statistics
   How would you describe your goals in teaching Probability and Statistics?
   In your opinion, how important is statistics/probability to students? How widely accepted are your views in the department? In the school/IB? Parents?
   How is teaching probability/statistics different/same than teaching other parts of mathematics?
   Please describe your experiences as a learner of probability/statistics.
   Please describe your experiences as a teacher of probability/statistics.
6. Current Research Project

What are your general impressions about this project?
What were you expecting to gain from the project (as well as your students)?
To what extent were your expectations met?
How would you rate student engagement?
What did you learn/observe during the project about your own learning/teaching?
What did you observe during the project about my learning/teaching?
What did students learn?
What needs improvement?
How do you envision teaching probability in the future?