ONCE AGAIN, WE NEED TO ASK,
"WHAT HAVE WE LEARNED FROM HARD EXPERIENCE?"

William Fleischman, Jack Crawford

Villanova University (USA)

william.fleischman@villanova.edu; jcrawf15@villanova.edu

ABSTRACT

In this paper, we discuss the disconcerting structural similarities between the series of radiation therapy accidents caused by the Therac-25 in the 1980's and the accidents and near-accidents involving the Boeing 737 Max aircraft in 2018 and 2019. These similarities concern engineering and software design, testing, hazard analysis, documentation as well as responses to accident reports. Considering the lapse of time between the two cases and the publicity attending publication of the 2017 revision of the ACM Code of Ethics, we reflect on the role of codes of ethics in computing and make several suggestions of measures that might enhance their effectiveness.

KEYWORDS: System failure, safety-critical software, engineering design, codes of ethics.

1. INTRODUCTION

The series of accidents caused by the Therac-25 computer-controlled radiation therapy machine is one of the most carefully studied and widely cited cases of accidents involving poorly conceived safety-critical software and deeply flawed engineering design. The Therac accidents are commonly and justifiably used as a fundamental case study in university courses in computer and engineering ethics and system safety. Although the accidents occurred more than thirty (and the design process more than forty) years ago, every aspiring computer or engineering professional should reflect on the deficiencies in software and engineering design, testing, safety analysis and documentation related to this case. In addition, they should think deeply about the ineffective and frequently dishonest responses of the device manufacturer to reports of harm to patients treated with the machine.

The currency of this case study is underscored by the striking similarities between the factors identified by Leveson and Turner (1993) in their investigation of the Therac-25 accidents and those, revealed in investigative articles in the recent press, relating to the contemporary series of accidents and near accidents involving the Boeing 737 Max aircraft.

In this paper, we begin by laying out in detail corresponding elements material to producing the harms that occurred in each of the two cases. We then reflect on the role of codes of ethics in the face of the persistence of identifiable patterns of unethical behavior and practice.

2. ONCE UPON A TIME … AND, DISCOURAGINGLY, ONCE AGAIN

There is a common ground circumstance that links the cases of the Therac-25 and the Boeing 737 Max. Each involved the re-design of a system that, because of an engineering decision, required the introduction of new safety-critical software. Design changes were significantly driven by economic factors. Subsequent similarities extend to deficiencies in testing and documentation, failure to consider carefully the “ecology of use” of each system, and, most disturbingly, a pattern of evasion and dishonesty by company personnel in response to reports of problems.

2.1. Engineering Decisions and Safety-Critical Software

The Therac-25, a radiation therapy machine or linac (linear accelerator) used in the treatment of cancer, was developed by Atomic Energy of Canada Limited (AECL). It was the successor to similar devices previously developed jointly by AECL with a French partner, CGR, under a collaboration agreement that had recently been discontinued. The Therac-25 had several novel features that made it an attractive investment for hospitals and cancer treatment centers. It was a single device that could deliver therapeutic doses of radiation in either electron or X-ray mode. Because of innovations in beam technology, it was a more compact device, yet able to deliver therapy at higher energy than earlier models. A further considerable economy resulted from the decision to substitute software for costly mechanical interlocks as the means of ensuring safe operation. (Leveson & Turner 1993)

Responding to innovations by Airbus, its main competitor in the passenger plane market, Boeing sought to redesign its 737 aircraft. The re-design involved replacing the engines common to earlier 737 models by more efficient, but larger and heavier, new engines. However, the size of the new engines dictated that their mounts be moved upward and forward on the wing in order to provide safe ground clearance for take-off. (Campbell, 2019) This created a problem in aerodynamics that Boeing engineers decided to solve through changes to the software system that controls flight characteristics of the plane. The supplemental software implementing this functionality was called the Manœuvering Characteristics Augmentation System (MCAS).

In each of these cases, the complexity of the control problem and the difficulty of developing a solution in software were vastly underestimated.

2.2. The Role of Economic Considerations and Governmental Regulation

For the Boeing 737 Max, as earlier for the Therac-25, there was a “frictionless” path to approval for commercialization under government regulations. All that was required was an affirmation by each of the companies that the systems were effectively identical to the earlier models that they replaced. In effect, this meant an assertion that performance characteristics of the systems were not affected by the inclusion of safety-critical software to replace or supplement existing control features.

The Therac-25 was approved for use under the FDA’s (U. S. Food and Drug Administration) pre-market notification process rather than the more rigorous and time-consuming process of pre-market approval in the early 1980’s (Leveson & Turner, 1993), a time at which the argument that hardware safety features of the device could be replaced by software perfectly equivalent in function might plausibly, if mistakenly, have been advanced.

For the 737 Max, the "frictionless" path involved retaining the 737 designation (hence the name Boeing 737 Max) so that pilots already certified to fly earlier 737 models would not be required to undergo lengthy and expensive training to be recertified on a new aircraft. However, this decision implicitly involved the assumption that changes to the aircraft's flight control software were of such a minimal nature that pilots would need only a short, self-administered computer course instead of expensive classroom time and training on a flight simulator to be properly prepared to fly the new plane. (Campbell, 2019)

2.3. Deficiencies in Testing and Hazard Analysis

The perfunctory nature of testing and hazard analysis performed for the Therac-25 by AECL engineers was brought to light by the careful investigation of Leveson and Turner (1993). By means of review of proprietary documents and interviews with personnel involved in the development process, several teams of journalists (Campbell, 2019; Gates & Baker, 2019; Nicas, Kitroeff, Gelles & Glanz, 2019) have uncovered similar shortcomings in the testing and analysis of hazards associated with the 737 Max software modifications.

2.4. Deficiencies in Documentation and Failure to Consider the Ecology of Use

The Therac-25 study cited glaring deficiencies in documentation both for internal purposes and in presentation of information to operators of the device who were provided only cryptic error messages and uninformative user manuals. Leveson and Turner (1993) remark tartly, "Software specification and documentation should not be afterthoughts."

Campbell (2019) and Gates and Baker (2019) relate how the pressure to certify the new aircraft and preserve the 737 type certificate led to serious deficiencies both in regard to documents filed with the Federal Aviation Authority (FAA), the cognizant regulatory agency, and, critically, in information provided for the training of pilots. Most seriously, Boeing introduced, and subsequently modified, a critical software control feature, MCAS, about which there was no mention in training bulletins prepared for pilots.

The effect of these deficiencies is magnified because of the disregard they indicate for the "ecology of use" of safety- and life-critical systems. In the case of the Therac-25 the lack of concern for providing meaningful information to operators who were low-level hospital personnel led to a pattern of tolerance of numerous apparently innocent machine malfunctions that infected hospital discipline at all levels. The resulting poor culture of care was implicated in all of the radiation overdoses inflicted on patients.

By contrast, pilots who fly the 737 Max are highly trained professionals. Nonetheless, the absence of information about changes to the aircraft's flight control software left them in uncharted waters under severe time pressure when that software mistakenly started to force the nose of the plane downward. The testimony of experienced pilots to the U.S. Congress was that "the terror and tumult of such a moment would defeat many of the world's best pilots," and "I can tell you firsthand that the startle factor is real, and huge." (Laris, 2019) Although a recent article blames the accidents on inexperienced pilots hired by newly chartered economy airlines (Langewiesche, 2019), Boeing knew of these practices and should have taken even more care in providing for this altered ecology of use.

2.5 Deficiencies in Response; Denial of Fault

After the first accident, in response to questions from the attending radiation physicist as to whether the Therac-25 was capable of malfunctioning and burning his patient, AECL personnel insisted this was impossible. Rather than investigating carefully, they maintained this posture and asserted that no one had been injured by the Therac-25, as one accident followed another, until there was definite confirmation that a patient had been burned by the device.

In a similar manner, Boeing denied that its control software was implicated in the first accident even though there was circumstantial evidence from a flight the day before that the software could create the conditions for precipitating loss of the aircraft. They attempted to conceal knowledge of the flaw in their control system as they tried to repair it. However, a technical bulletin posted on the company’s online portal for pilots and airlines, that made oblique reference to the conditions of the first accident without directly identifying MCAS, generated such a volume of angry demands for additional information that Boeing had to admit there was something fundamentally wrong with the aircraft and name and explain the nature of the faulty modification. (Campbell, 2019)

2.6. Deficiencies in Response; Unfounded and Irresponsible Claims

In one notorious episode involving the Therac-25, AECL engineers inspected an accident site, could not replicate the conditions that produced the malfunction, but speculated as to a possible cause. AECL engineered a “fix” for the hypothetical fault and then made the preposterous announcement that “analysis of the hazard rate of the new solution indicates an improvement over the old system of at least *5 orders of magnitude* [emphasis added].” (Leveson & Turner, 1993)

In its safety analysis of MCAS, Boeing identified several possible failure modes. One particular mode associated with the actual accidents was designated as “hazardous,” something with the potential to cause serious or fatal injuries to a small number of people not, however, resulting in loss of the plane itself (a “catastrophic” failure.) Boeing calculated the probability of this failure as approximately one every 223 trillion hours of flight. Gates and Baker (2019) remark acidly, “In its first year in service, the MAX fleet logged 118,000 flight hours. On the basis of this analysis, Boeing downgraded the number of sensors required to confirm the condition from two to one, thus creating circumstances that increased dramatically the likelihood of this failure due to malfunction of or damage to the single sensor involved.

In cases of such breath-taking obtuseness, it is difficult to say which is the greater fault – failure to analyse correctly the true sources of danger, or the recourse to incomprehensibly large numbers to provide a misleading quantitative “fig leaf” of rationality for an unfounded assurance of safety.

2.7. Pressures Generated by the Rush to Market

Although Leveson and Turner do not comment directly on this, the fact that earlier Therac models had been collaboratively developed suggests that AECL may have been anxious to pre-empt possible competition from CGR by expediting the introduction of the Therac-25. This would explain in part the deficiencies in testing, hazard analysis and documentation they uncovered.

In the case of the Boeing 737 Max, these pressures were explicit. Boeing rushed to prevent Airbus from securing market dominance in sale of single-aisle passenger aircraft. Several authors detail the accelerated pace of releasing blueprints and pressures on all aspects of engineering, software development, and testing, all citing internal sources at Boeing. Even an experienced commercial pilot for a major airline was aware of the effects of Boeing's procrustean efforts to preserve the 737 type certificate for the new aircraft. (Campbell, 2019; Gates & Baker, 2019; and Travis, 2019)

2.8. Latest Developments As We Go to Press

With the Therac-25, we have the benefit of closure. In the course of the series of accidents, several software errors that were directly connected to the instances of severe radiation overdose were uncovered. In reaction to the evasive and unsatisfactory responses of AECL, a Therac-25 user's group was constituted with the goal of providing more transparent communication between users and AECL as well as for the timely exchange of information about protective measures adopted by individual treatment centers. Eventually, the combined pressure of the Therac-25 user's group, and the regulatory agencies of the U.S. and Canadian governments forced AECL to address and correct the serious problems affecting the operation of the Therac-25.

In the case of the Boeing 737 Max accidents, the story is still unfolding. The 737 Max has been taken out of service and is undergoing extensive study, modifications, and testing in order to establish its safety as a precondition for recertification. During this process, three new software problems have been uncovered, one of which, though unrelated to MCAS, "could cause the plane to dive in a way that pilots had difficulty recovering from in simulator tests." (Savov, 2019) (Pasztor, 2020) (O'Kane, 2020)

One recent development, however, establishes another noteworthy point of correspondence with the case of the Therac-25. After steadfastly resisting this measure throughout the process of development, marketing, and introduction into commercial service, Boeing has finally admitted that simulator training is recommended and will be necessary for 737 Max pilots once the plane is again declared safe to fly. (Hawkins, 2020)

3. A MYSTERY

Throughout the period of investigation into the background of the Boeing accidents, there was one question that continually and insistently arose in our thoughts. Why was it, how could it be that at no point in the design process for the 737 Max did anyone highlight the danger of relying on a single sensor to indicate the problematic nose-up flight condition that engineers feared might cause the plane to stall and, if not corrected, cause the loss of the aircraft?

In fact, as the result of congressional investigation and tenacious reporting by several teams of journalists, leading to disclosure of internal Boeing documents, we now know that this problem was broached three years before the 737 Max crashes by at least one individual, someone identified only by his or her function as an Aero-Stability & Control advisor. (Helmore, 2019) Although we have inquired of the author of that report as to the specific engineering or computer background of this individual, we have yet to receive a response (and reluctantly conclude that none will be forthcoming.) In the absence of any further information, we consider that it is most likely that he or she is an aeronautical or mechanical engineer.

That this warning, three years in advance, about the eventual proximate cause of two fatal 737 Max crashes appears to have dropped like a stone to the bottom of the ocean seems consistent with reporting on hundreds of additional pages of internal documents recently disclosed to congressional investigators that "reveal chaos and incompetence at 737 Max factory" and indicate that Boeing executives themselves "mocked their [FAA] regulator, joked about safety and said the Max had been 'designed by clowns.'" (Rushe, 2020) One could be forgiven for regarding with just the most infinitesimal grain of skepticism the company's latest attempt to salvage the aircraft's reputation through a series of videos currently being produced maintaining that Boeing is committed to a culture of aviation safety. (Horton, 2019; Boeing, 2020)

The danger with this facile characterization of Boeing as a corporation gone (temporarily) rogue is that it induces forgetfulness of the fact that actions of ethical weight and serious human consequence are not taken by corporations but by individual human beings. Further, in this case, such a perspective obscures an important question relating to shared responsibilities of technical professionals.

4. REFLECTIONS ON CODES OF ETHICS

If we make the most favourable assumptions about the motivation and actions of computing professionals, comparison of the Boeing and Therac-25 cases suggests that at least some of the problems they encounter are rooted in the nature of their interactions with engineers and professionals from other disciplines, the latter possibly acting in a supervisory role. The revised ACM Code of Ethics does speak of the duty to report risks, but in a document of many words, emphasis on this point is lacking and there is no explicit reference to the type of risks that arise in the interactions to which we have alluded.

We believe computing professionals have certain explicit proactive responsibilities in regard to system development tasks they implement where specifications are set by other engineers and managers. **"Are you really asking me to write code to implement a potentially catastrophically dangerous manoeuvre of the aircraft on the basis of input from a single, fragile and easily compromised sensor?"** This, ultimately, would seem to be the critical, unasked question that ought to have been raised by the software development team working on MCAS. Certainly, if members of this team were appropriately informed – either through direct participation in the engineering discussions concerning the potential problem of stalling caused by the aerodynamic characteristics of required upward and forward placement of the new larger and heavier engines, or through documentation in the software specifications indicating the nature of the sensor input that would trigger the dangerous nose-down manœuver – then a large measure of blame for the loss of life in the Boeing accidents accrues to this team for failure to insist that this single point-of-failure condition be modified.

The responsibility is more subtle, and the weight of blame shifted dramatically toward the aeronautical and mechanical engineers responsible for the engineering design of MCAS, if the nature of this critical single point-of-failure design element was concealed or omitted in the specifications provided to the team responsible for writing the code that implemented this feature of MCAS.

Here, the affirmative responsibility would seem to require active questioning on the part of the software development team concerning the engineering considerations and calculations on which the specifications were based. In light of the specious reasoning and the preposterous quantitative claim regarding the likely occurrence of the relevant failure mode (see sub-section 2.6), it is far from certain that questioning by the software engineers would uncover the danger. On the other hand, the requirement of articulating the reasoning underlying the engineering specifications to an audience having an active interest in understanding potential hazards might well lead someone to say, **“Wait! Are you really asking me to write code to implement a potentially catastrophically dangerous manoeuvre of the aircraft on the basis of input from a single, fragile and easily compromised sensor?”** or even, **“Wait! Are we really asking you to write code to implement a potentially catastrophically dangerous manoeuvre of the aircraft on the basis of input from a single, fragile and easily compromised sensor?”**

At any rate, the scenario depicted in the preceding paragraph – in cases where software engineers are developing life- or safety-critical systems based on specifications laid down by engineers and professionals from other disciplines – strikes us as identifying a condition that merits prominent mention and an unequivocal statement to the effect that computing professionals have an affirmative responsibility to insist on appropriate disclosure concerning potential critical points of failure in code they are commissioned to write. Given the nature of the tasks they are likely to be given, we think inclusion of a warning of this nature is essential in order for a code of ethics to have any meaning or force, at least in regard to holding paramount the safety and well-being of the public.

If the objection is raised that such a condition is unrealistic at the contemporary interface of engineering and software engineering practice, the sceptical observer might be forgiven for advancing the opinion that the current diffuse, word-logged, and self-apologetic ACM Code of Ethics has very little value in regard to what one would assume is its most critical purpose: protecting the health, safety, and welfare of the public.

We believe further that including illustrative case studies highlighting these types of interactions, with explicit reference to real world experience, would be useful in alerting computing professionals to the pitfalls they are likely to encounter in such situations. We suggest an approach similar to that of the American Society of Civil Engineers (ASCE) whose code of ethics website includes a sidebar featuring persuasive case studies based on the real experiences of practicing civil engineers. (American Society of Civil Engineers, 2017) In the present context, for example, a compact comparison of common problematic factors in the Therac and Boeing cases might be effectively presented among the case studies accompanying the ACM Code of Ethics.

5. GOVERNMENT IS THE PROBLEM

Ever since Ronald Reagan told us that “The government’s not the solution. The government is the problem,” and “The most terrifying words in the English language are: I'm from the government and I'm here to help,” we have been conditioned to take as the default assumption that, to the extent possible, government regulation should be curtailed. At the present moment in the U.S., we are in the throes of a veritable bacchanalia of disparagement and nullification of long-standing governmental regulations designed to protect the air we breathe, the water we drink, the land we inhabit (including public lands set aside for the enjoyment of multitudes), and the climate in which we and our children and grandchildren will live. The scientific basis for the abolition of these inconvenient regulations is abundantly clear: Greed is good, especially when it concerns the interest of extractive industries and despoilers of the public treasure.

We would like to suggest that these two histories of fatal accidents involving badly conceived technology (specifically, software) tell a different story and provide a badly needed corrective to the reflexive mantra, “Government is the problem.” Each, in its own way, reveals something noteworthy about the limitations and virtues of government regulation and the hazards of a regime of laissez faire.

5.1. Government Regulation and the Therac-25: the FDA and the CRPB

As we have already noted, the Therac-25 was approved for use under the FDA’s pre-market notification process rather than the more rigorous and time-consuming process of pre-market approval in the early 1980’s (Leveson & Turner, 1993). This meant that all AECL had to do was establish or assert that it was substantially equivalent in safety and effectiveness to a product already on the market. In the wake of the Therac-25 accidents, the inadequacy of this regulatory protocol was clearly understood. The idea that one could replace protective measures built around hardware interlocks by software controls and, by means of software alone, seamlessly achieve the same degree of safety, is inconsistent with our current understanding of the limitations of software.

The relevant question about the adequacy of the regulatory process when the Therac-25 was approved for use is, “Where, in the early 1980’s, would one have expected to find the expertise necessary to evaluate an application made under pre-market notification in which the safety capabilities of software controls were equated with those of hardware interlocks?” The realistic answer is that individuals with expertise of that nature would be much more likely to be working in industry or private enterprise than for a regulatory agency of the government. From this standpoint, the balance of responsibility would seem to rest more heavily on the manufacturer, AECL. In applying to have the Therac-25 approved under pre-market notification, its engineers asserted a questionable equivalence that they were in a better position to understand than regulatory personnel. If, in fact, they did not appreciate the risk, this was a lapse which they subsequently compounded through their dismissive responses to suggestions that the Therac-25 had caused injuries to several patients. If, however, they were aware of that risk, their actions were not merely irresponsible but criminal as well.

It is noteworthy that the one individual who, according to every account, “got the problem right” from the very beginning was Gordon Symonds, head of the division of advanced X-ray systems of the Canadian Radiation Protective Bureau (CRPB). Perhaps the nature of the CRPB, having a narrower focus than the FDA, whose mandate covers broad and disparate aspects of public health and safety, made it more likely that there would be someone on its staff in a position to identify the source of the problem with the Therac-25.

In his reports on the second Therac accident, which occurred at the (Hamilton) Ontario Cancer Foundation, Symonds expressed prudent skepticism about the advisability of entrusting safe operation of the Therac-25 to software alone and, at that early moment, made several of the crucial recommendations for ensuring safe operation of the device that were eventually incorporated (two years and three patient deaths later) into the final Corrective Action Procedure (CAP) that was imposed on the manufacturer by Canadian and U.S. authorities and the Therac-25 Users Group before its use in radiation therapy was again permitted. (alternatively, "before the recall and suspension of use was lifted.") (Leveson & Turner, 1993)

At any rate, "[o]nce the FDA got involved in the Therac-25, their response was impressive, especially considering how little experience they had with similar problems in computer-controlled medical devices." (Leveson & Turner, 1993)

5.2. Government Regulation and the Boeing 737 Max: the FAA

In the present moment of wholesale abandonment of a commitment to the value of governmental regulation, it is difficult to imagine a story that more dramatically conveys the irresponsibility of this stance. (On second thought, there are probably many equally illuminating stories that carry the same urgent warning but since they mainly involve poor children affected by toxic levels of lead in urban water supplies, or economically disadvantaged people, often predominantly people of color, living in the vicinity of waste fields where cancer-inducing toxic chemicals or coal ash are routinely buried under current, permissive "environmental" regulations, these stories don't rise to the same urgent level of concern as the Boeing accidents for important people like us for whom air travel is a necessity of life.) (Lartey & Laughland, 2019) (Costley, 2020)

Given the unequal balance in expertise between Boeing and the FAA, it has long been customary for some regulatory activity to be delegated back to qualified Boeing personnel. This was an arrangement that worked well as long as the priorities of the regulator and manufacturer were satisfactorily aligned – concern for the safety of the public being of paramount interest to both parties.

However, when reductions in funding for most U.S. regulatory agencies began to affect personnel levels at the FAA and their capacity to adequately oversee the full range of regulatory activity, the balance of responsibility began to shift in significant degree toward *de facto* self-regulation by Boeing. In this process, the reciprocal respect concerning competence and integrity that had existed between Boeing and the FAA based on a shared commitment to the safety of the public must have begun to erode in dramatic fashion. How else explain language like that found in reports describing Boeing employees expressing open contempt for regulatory personnel and process? (Rushe, 2020)

The detrimental effect of the FAA policy of acquiescence in *de facto* Boeing self-regulation is further shockingly demonstrated by its failure to act on an in-house analysis after the first fatal 737 Max accident that anticipated the likelihood of additional tragedies. "US regulators allowed Boeing's 737 Max to keep flying even after their own analysis found the plane could have averaged one fatal crash about every two or three years without intervention." (Rushe, 2019)

5.3. Where Does This Leave Us?

Given the clear evidence of the failure of a scheme that privileges self-regulation over rigorous governmental scrutiny, it is difficult to pronounce even a neutral judgment on the relentless dismantling of government oversight in the interest of public safety. "Nor is oversight likely to get much of a boost from the Trump administration. Donald Trump has used two executive orders to cut regulatory oversight and hand more of that supervision over to businesses. Trump's 2019 budget proposed an 18% cut to the transportation department." (Rushe, 2020)

Let us try to put a fine point on it: This is criminal recklessness on the part of the author of this policy, but also criminal dereliction of responsibility on the part of the U.S. Congress in failing to act to reverse such a dangerous course. In the end, someone has to say, amending in just the subtlest shading the timeless wisdom of Ronald Reagan, "**Government is indeed the problem – when it is a matter of government by corrupt, venal, foolhardy imbeciles**."

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