Identifying Pitfalls of Regulating Cadmium in Technology

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

My capstone project for my last year of undergraduate study is a collaboration with Rolls Royce on optimizing the composition of zinc-nickel (Zn-Ni) coatings for protecting steel parts from corrosion. In the past, cadmium has been used for this purpose, but the goal is to phase out the metal due to its toxicity. The results of the project are promising so far, and to me it's begged the question: why were engineers using cadmium to begin with?

Corrosion is the process of environmental exposure causing reactions which remove material from the surface. This happens spontaneously to metals when exposed to water, as a common example, which together experience electrochemical reactions reversing the metals to a state similar or identical to their mineral forms (Jones, 1996, p. 5). Environmental coatings are used to protect metals from corrosion by serving as a barrier on the surface. Cadmium has served as an effective industry-standard sacrificial coating, a layer which corrodes more favorably than the underlying material, that performs well in saltwater environments and has good mechanical properties. However, cadmium is a carcinogenic heavy metal which increases cancer risk in exposed individuals, particularly in those working directly in industries involving its use (IARC, 2012; Mead, 2010).

In this paper I argue that while the toxicity and potential of replacing cadmium has become understood, elements of uncertainty have led to risk management where regulation keeps pace with technological readiness more than scientific knowledge. Despite research on health risks of cadmium exposure beginning over a century ago, government and industrial interests have only enacted regulations in recent decades and still have allowed notable instances of cadmium exposure. In this study, I researched why it has taken decades to establish meaningful regulation to protect people from excessive cadmium exposure. I examined journal articles on cadmium toxicity and documents covering important regulations and technologies featuring cadmium. First, I provide an overview of the literature on cadmium toxicity, regulation, and usage. Next, I analyze government reports and regulation on cadmium to ascertain the timeline of and decision making behind major policy. I find that while there is enough evidence to reasonably determine cadmium's toxicity, there are difficulties due to the nature of its exposure and health impacts which have limited the conclusiveness of past research. In addition, while there is regulation limiting cadmium use and exposure, standards take time to implement and are ultimately arbitrary, and while cadmium is being phased out of technology, it remains practical enough to justify its use in select applications. Finally, I end with a discussion of how this research reinforces the need for policy to continue reflecting scientific knowledge of toxicity even with its flaws.

Literature Review

Cadmium is a known carcinogenic substance which can increase the chance of health complications even in minute quantities. Exposure comes from either ingestion, as cadmium can enter the food chain from contaminated soil or water, or inhalation of fumes containing cadmium dust. After entering the body, cadmium interferes with normal functions, typically causing problems in the kidneys, bones, and lungs (ATSDR, 2023). Occupational studies of workers exposed to cadmium have been performed since the 1950s. Hours after individual cases of acute exposure, severe symptoms relating to respiratory irritation and inflammation have been reported. While these symptoms did not manifest in workers exposed to lower levels over longer times, there have still been cases of lung conditions relating to chronic shortness of breath as well as increased deaths to respiratory disease in workers exposed over 5 years (Faroon et al., 2012, pg. 50, 73).

The research on cadmium toxicity across the world's scientific community arguably dates back to 1858 with one study on acute gastrointestinal and delayed respiratory symptoms among users of cadmium carbonate powder and another experimental toxicology study in 1919. Animal experiments and case studies throughout the 20th century found cadmium and cadmium-containing compounds to be damaging to tissue (Nordberg 2009; Pařízek, 1957; Miller et al, 1969). The National Health Survey Act was passed 1956 to legislate a continual survey of illness and disability in the United States leading to the present; an emphasis was added in 1970 to also monitor nutrition (CDC 2019). Since then, cadmium has been studied as a substance present in daily intake through inhalation and ingestion as early as the 1970s (Friberg, 1971, pp. 24-33).

Despite the research body on cadmium toxicity, it was not until 1979 that Sweden passed one of the first cadmium bans, and even then, they delayed the ban's enactment until 1982 anticipating an overwhelming number of applications for exemptions (Nilsson, 1979; Hinrichsen, 1980). The EU banned its use in most plastics in 1992, allowing an exception for polyvinyl chloride until 2011 when they added cadmium use in jewelry and plastics to the substances banned under the Registration, Evaluation, Authorization & Restriction of Chemical substances (REACH) chemical law (Nilsson, 1979; Erickson, 2011). While there was awareness of cadmium's toxicity and government service to monitor its effects on the public, there is yet to be a national ban in the US on cadmium use. To this day, scientists study the health implications of cadmium exposure and legislators attempt to regulate its use and emissions (Sovičová et al, 2019; "Minnesota, USA, Regulates Chemicals in Products," 2023).

While there has been research indicating cadmium is carcinogenic and some regulation has been enacted to restrict its usage and limit allowable exposure, the metal continues to appear in certain applications. One area where cadmium is yet to be phased out completely is in environmental coatings for protecting mechanical components exposed to strongly corrosive environments, the most notable example being aircraft fasteners (US Geological Survey, 2024). Another use is in nickel-cadmium batteries, which were the state-of-the-art for mobile electricity storage before lithium-ion batteries became competitive, and they are still a viable technology due to their stability (US Geological Survey 2024; Blumbergs et al., 2021). A third major technology is cadmium telluride (Cd-Te) solar panels, which use cadmium as part of a semiconductor on par with silicon-based solar panels and make up around 16% of the US photovoltaic market (Basore et al., 2022). Aside from intentional appearances of cadmium in technology, exposure to the metal can also occur because of pollution or accidental inclusion in products. Cadmium can end up in the soil and water through man-made routes including zinc-refinement and phosphate fertilizers (ATSDR, 2023; Faroon et al., 2012, pg 323). There have also been cases of accidental exposure such as recalls of toy jewelry and drinking glasses after the discovery of substantial cadmium levels (Mead, 2010).

Cadmium has been used for several important engineering materials, but it is also technologically possible to replace the metal. One major use for cadmium in the past has been red pigments in paints and plastics. However, cerous sulfide is a viable alternative to cadmium in plastics and has been used to replace it since 1999 (US Geological Survey, 2024). Ni-Cd batteries are also still in production even with lithium-ion batteries becoming increasingly competitive (US Geological Survey, 2024; Blumbergs et al., 2021). Similarly, Cd-Te solar panels are deployed even as the majority of photovoltaics both in the US and the world are made with silicon semiconductors (Basore et al., 2022). In the case of the environmental coatings which prompted me to engage in this research, cadmium remains useful in extreme environments as a sacrificial coating for steel alloys. Cadmium corrodes preferentially to steel while not causing embrittlement (any process causing a material to fracture under less repeated stress) and having a long operational lifetime under exposure to salt water. There aren't many alternative materials, as materials such as beryllium are also toxic and others such as magnesium and pure zinc corrode too readily. However, Zn-Ni coatings with between 10-18% nickel by weight can have a corrosion rate comparable to cadmium without its toxicity (Gaydos 2007). The research and development are ongoing to eliminate embrittlement with a Zn-Ni coating, hence cadmium still remains viable for specific applications such as aerospace.

To address the seeming discrepancy between knowledge of toxicity and implementing change in policy and technology, I need to ascertain a collection of important dates for several intersecting timelines. This research builds off Trevor J. Pinch and Weibe E. Bijker's social construction of artifacts: a Social Construction of Technology (SCOT) approach is necessary for considering the interconnectedness of the places cadmium appears and the stakeholders between industry, government, and the consumers (Pinch and Bijker, 1984, p. 410-412). The SCOT framework considers relevant social groups, the distinct collections of individuals which a technology has shared meanings. The technology in question has some degree of stability, where the fundamental details of a technology remain unchanged, and a degree of closure, where relevant social groups see a problem as being solved (Pinch and Bijker, 1984, p. 424-425). A technology such as environmental coatings can be considered relatively stable under this framework since the design remains largely unchanged; however, the desire to phase out cadmium reveals an unsolved problem prompting research and development until the technology approaches closure.

Methods

The first area I considered was toxicity research on cadmium, which involved tracking what subjects and methods were used to assess toxicity and when the research was published to gauge how certain the overall findings were over time. I read through scientific journal articles dating back to the 1970s as well as national reports on cadmium toxicity data such as the Center for Disease Control and Prevention (CDC) Toxicology Profile of Cadmium and the Environmental Protection Agency (EPA) National Report on Human Exposure to Environmental Chemicals. Second, I looked at government regulations on cadmium use such as current US Occupational Safety and Health Administration (OSHA) standards for exposure to toxic metals to find when they were enacted and how significantly they controlled its use. These two elements together serve as a policy analysis to determine the time needed for the science of cadmium toxicity to influence policy. Finally, I investigated who used cadmium or otherwise has been impacted by the regulations and how much push-back did they show. This included examining the US Geographic Survey's assessment of cadmium use and potential for substitution over time. For details on how actors have pushed back against regulation, I considered the news surrounding Sweden's cadmium ban decades ago and the 2016 lawsuit against the EPA after the agency relaxed its standards. In reviewing this evidence altogether, I perform a historical analysis using SCOT to highlight major points in the story of cadmium and why it has been used in technology for as long as it has.

Results

While cadmium is widely accepted as being a carcinogenic substance, one issue in transferring scientific findings to regulation was the uncertainty in the extent of how toxic the metal is. Animal experiments provided a more ethical and practical approach to studying the vectors and magnitudes of cadmium exposure as opposed to directly studying its toxicity to people (Roe et al., 1964; Satoh et al., 2002). They were useful for establishing how cadmium can affect human health as health complications occurred in animal subjects, but there is still a gap to bridge to understand the degree of toxicity to people. Case studies are useful for providing data on humans, but they are difficult to generalize for regulations because the data is harder to find statistical significance for due to limited sample size. In the EPA's 1987 Chemical Assessment Survey, while there was sufficient evidence for carcinogenicity in animal experiments and increased cancer risk among cadmium smelter workers, it was concluded that there was "limited evidence of human carcinogenicity", which show us how scientific rigor is harder with human subjects (EPA, 1987, pg 5). In addition, people exposed to cadmium are often also exposed to other toxic metals as confounding variables. In the CDC's Toxicology Profile for Cadmium, the authors state how confounding effects limit the interpretation of scientific studies including several which found significantly increased occurrences of lung cancer among workers (Faroon et al., 2012, pg 15, 100-101). It is reasonable to conclude that exposure should be limited as much as possible when accounting for the correlations to health complications observed among exposed workers and the body of scientific data including animal studies. At the same time, the literature must acknowledge the weaknesses in the research in the interest of scientific integrity, and this has translated to government agencies reporting that cadmium is a probable carcinogen without being able to say definitively.

A key detail slowing down the regulation of cadmium specifically is how health complications occur due to accumulation in the body over years. One method of measuring cadmium accumulated in the body is measuring the amount of the protein β_2-microglobulin in urine, which one notable paper by Elinder et al. (1985) used to study a group of factory workers. This study found that the cadmium-induced protein appeared in greater concentrations among workers exposed for longer, and cadmium levels remained high even years after exposure ceased (Elinder et al., 1985). The CDC released its first National Report on Human Exposure to Environmental Chemicals in March 2001, detailing information of environmental chemicals including cadmium in the US population. This report compiles findings from the National Health Examination Surveys which collected extensive data on the health of subjects including baseline cadmium levels among the general population (CDC, 2019; CDC, 2001, pg 19). This data is useful for gauging what typical levels of cadmium look like, and so elevated levels can be considered generally worse for an individual's health assuming that a representative US subject has had a "safe" amount of exposure. From the perspective of the researchers and the representatives of the CDC, the data collected over years provides workable, albeit arbitrary, guidelines for how much cadmium exposure is acceptable.

While it can be reasonably inferred from the science of cadmium toxicity that cadmium should be protected against, regulations are subject to the influence of those restricted as government agencies attempt to set standards to protect against exposure. Sweden was a very early example of extensive government regulation as the country passed a ban of major uses in 1979. This decision did not go without resistance and was pushed back two years, starting instead on July 1, 1982 because of "administrative problems" anticipating on the order of 10,000 requests for exemptions (Nilson, 1979). In addition, the Association of the German Mineral Paint

Industry released two letters in October and December 1979 which asserted that banning cadmium in pigments and plastics would cause more harm than good, allegedly reducing emissions by only 1% (Nilsson, 1980). The fact that Robert Nilsson, the then-Head of Toxicology Section of Sweden's Environmental Protection Board, needed to write an article refuting the European cadmium industry's claims about the negative impact of the cadmium ban shows that industry had a significant impact on its implementation. From the perspective of SCOT, this conflict highlights the clashing between advocates for environmental protection, who view cadmium as a toxic substance needing regulation, and advocates from industry, who view the metal as technologically and economically important.

The consistency in cadmium regulations comes from the arbitrary nature of deciding how much risk is acceptable. Under the US OSHA entry its Occupational Safety and Health Standards for cadmium, the agency provides Separate Engineering Control Airborne Limits (SECALs) deciding the maximum allowed employee exposure in major cadmium industries. These SECALs are understandably higher in processes working directly with the material than adjacent processes (50 $\mu g/m^3$ vs 15 $\mu g/m^3$), although there is also an exception for employers demonstrating that "the employee is only intermittently exposed" and still ensures that employees are not exposed above the permissible exposure limit of 5 $\mu g/m^3$ more than 30 days in a 12-month period (OSHA, 2020, 1910.1027(f)(1)(iii)(A)). To regulators and employers, this standard provides a clear and widely applicable measure for whether workers are adequately protected from cadmium exposure on the job. However, the standard is only binding in the eyes of the law which sets a single point as the maximum safe amount of exposure while actual exposure and health consequences are a gradient. One worker exposed just below the 5 $\mu g/m^3$ of cadmium can be considered at lower risk than another worker exposed above the threshold and is compliant with OSHA policy, but any amount of exposure can be considered a health risk because there is no single amount of cadmium exposure where a person is completely safe.

The arbitrary nature of regulatory standards is highlighted by how they can be changed, especially if reversed. The EPA's first criteria for cadmium was instated in 1980 under Section 204(a), and later the agency updated the criteria in the years 1985, 1995, 2001, and 2016 in accordance with the Clean Water Act to update standards reflecting on the latest scientific knowledge (*Center for Biological Diversity v. US EPA*, 2022, pg 16). The effect of these updates varied in how freshwater and saltwater concentrations were changed. The revisions made in the 2016 update were important because the criteria became slightly stronger overall but weakened the standard for chronic freshwater exposure, potentially threatening already endangered species. This led to a lawsuit in 2022 filed by the Center for Biological Diversity, a charity organization for education about and protection of endangered wildlife, because the EPA did not consult the Fish and Wildlife Service and National Marine Fisheries Service about cadmium levels even though most of the cadmium in water results from human activity (*Center for Biological Diversity v. US EPA*, 2022, pg 2). District Court for the District of Arizona ruled that the EPA violated the Endangered Species Act (Connor, 2023). The decision reflects hope that the EPA will maintain due diligence and make sure to consult relevant authorities while deciding allowable amounts of toxic substances. However, it also reflects a conflict between different entities in how toxic cadmium is viewed as and how much pollution can be allowed in the environment.

Some of the inconsistencies in cadmium regulation across the world stems from varying attitudes across different governments. I find Sweden an important point for comparison because of how consistently strong the country's policy on environmental protection has been. They were the first country to pass an environmental protection act in 1967, and for the past decade Sweden has scored in the top 10 countries worldwide on the Columbia and Yale University's Environmental Performance Index (EPI) (Sweden Institute 2023; Block et al., 2022). Sweden's performance in environmental protection in general and towards regulating cadmium shows how the country overall views the potential benefits of using cadmium as less important than tolerating its toxicity. This isn't to say that the US completely neglects environmental protection, but the country has room for improvement as evidenced by a global rank of 43rd best EPI as of 2022 (Block et al., 2022). For regulating cadmium specifically, the laws in the US are less comprehensive than Sweden and the EU. There is the Federal Hazard Substances Act (FHSA) which has the power to ban hazardous substances such as lead in excess concentrations, but there is no specific mention of cadmium (Consumer Product Safety Commission, 2011). Regulation often falls to individual states such as with California's Proposition 65 and Minnesota's more recent Environmental Omnibus Bill (Office of Environmental Health Hazard Assessment 2024; Office of the Revisor of Statutes 2023). Aside from the division of federal and state governments slowing down progress towards unified policy, the regulations towards cadmium in the US are indicative of a more moderate overall attitude. Cadmium is noted as a toxic substance with some states taking more active stances against its use, but current legislation suggests that cadmium use is still justifiable enough in some applications.

Cadmium has been difficult to consistently regulate because it remains useful enough to justify its continued use even in applications with suitable substitutes. Ni-Cd batteries remain commercially viable alongside lithium-ion batteries thanks to their durability, lifetime, rapid discharge rate, and low cost (Blumbergs et al., 2021; US Geological Survey, 2024). In the case of photovoltaic energy generation, CdTe solar panels are less efficient at generating electricity than monocrystalline silicon systems. However, they have efficiency comparable to multicrystalline silicon, and their reduced cost allowed CdTe panels to hold approximately 16% of all the US photovoltaic capacity between 2010 and 2020 (Basore et al., 2022). The framework of Pinch and Bijker's SCOT warns against viewing technological innovation as linear because hindsight can easily lead to conflating distinct paths along a technology's development (Pinch and Bijker, 1984, pg 441). With both rechargeable battery and photovoltaic technologies, there are multiple material systems engineers can consider the performance characteristics and availability of for a given application. To engineers, cadmium-based technologies as a possible solution to design problems with strengths and weaknesses. For environmental coatings, cadmium can even be the best solution for protecting against corrosion. Part of the difficulty in replacing cadmium for the purpose of these coatings is that there are few alternative metals which are also electrochemically active enough (Gaydos 2007). Alternative coatings like Zn-Ni are in theory viable and show promise in practice. However, optimizing this solution is an ongoing affair: speaking both generally and having worked on a capstone project about this topic, developing materials for extreme environments can be greatly time-consuming and justifies cadmium's continued use as an existing solution. Without a total ban on cadmium, the metal will continue to be used and regulations need to balance protecting workers and others potentially exposed and allowing an acceptable amount of risk from using cadmium at all.

A conclusion one could reach after reviewing this information would be that policy regarding cadmium toxicity is driven more by scientific findings on the effects of exposure on human health, and the technologies where cadmium can be useful simply adapt in reaction. This is not an entirely flawed assessment as under Pinch and Bijker's theory of SCOT, relevant social groups can and with adjust the development of technology to reflect changing desires. However, we must remember that technology is also a driving force reflecting these groups. Cadmium has been used in technology because it has properties and availability which engineers found to justify its use, hence why it is still used for some environmental coatings. In the same vein, cadmium is being phased out as it is deemed technically viable and justifiable, whether its use is broadly prohibited as Sweden decided decades ago or it becomes completely replaceable as Rolls Royce currently decides. There is plenty of interplay between the science and technology behind cadmium use, but ultimately, I still hold that technological readiness drives the extent of regulation more because cadmium exposure would not be a problem for science or policy to address without its introduction by engineers as a technological solution.

Conclusion

I hope that this research shows how the difficulties of building science and developing technology can inform regulation as policymakers attempt to best decide acceptable amounts of cadmium. Just as engineering often works with changing knowledge, policy is arbitrarily made attempting to best account for current information and needs in principle. It is prudent to continually listen to what science says as it improves and generally ere on the side of caution to appropriately manage risk to human life considering an evolving knowledge base. Future research may include cases of the regulation of other toxic substances and delve into the specific interactions between policy and engineering decisions. There is also work to be done to account for the political and cultural differences of how science and policy develop across different countries, which ended up outside the scope of this study.

Science is a useful framework for building knowledge of a universe including complex systems such as the human body, which is important for making educated decisions regarding our continued existence. Complex problems can lead to imperfect science, but it often needs acting upon, nonetheless. Cadmium is toxic to the human body, and even with weaknesses in the science, this is a reasonable enough conclusion to justify measures to protect people from exposure and phase out its use in technology. As scientists and engineers, we strive to do our best to objectively describe our findings and support the well-being of society even in the face of imperfect and incomplete information. It can be easy to be pessimistic about the frustrations of policy and technological development: I often worry about the future as I prepare to graduate as an engineer and enter academia. As long as we remember that the future does not happen everywhere at once, we can see that steps are being taken to continually improve society and we are capable of facilitating positive change.

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