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# Does a higher liability limit reduce the risk-taking of nuclear power plants?

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**Abstract**

Risky industries, such as nuclear power plants, typically face a limited liability in the event of accidents. This has caused some concerns that owners would take excessive risks in order to increase short-term profits. An empirical study has been done on reactors in the U.S., where the focus is on a change in the liability limit in 2003. The aim is to investigate whether an increase in the liability limit leads to less risk-taking by the nuclear power plants—with safety performance (risk-taking) being measured by unplanned stops and worker radiation exposure. Due to the lack of a true control group, the plants are separated by ownership in order to test the model under different incentive structures. It is found that divested plants decreased unplanned stops, and non-divested plants decreased worker radiation exposure, in response to the increased liability limit. The result is dependent on some assumptions which can be tested by including additional, albeit difficult to measure, control variables such as safety regulations.

Keywords: Nuclear safety, liability regulation, liability insurance
JEL: C33, L51, Q48

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## Abbreviations

| | |
|---|---|
| BWR | Boiling Water Reactor |
| EAF | Energy Availability Factor |
| EL | Energy Loss |
| NPP | Nuclear Power Plant |
| NRC | Nuclear Regulatory Commission |
| PUF | Planned Unavailability Factor |
| PWR | Pressurized Water Reactor |
| REG | Reference Energy Generation |
| RUP | Reference Unit Power |
| UCLF | Unplanned Capability Loss Factor |
| XUF | External Unavailability Factor |

## Mathematical notations

| | |
|---|---|
| $c_v$ | The variable cost of producing energy |
| $c(m)$ | The cost of doing $m$ (see definition below) |
| $c_r(m_r)$ | The cost of doing $m_r$ (see definition below) |
| $c_s(m_s)$ | The cost of doing $m_s$ (see definition below) |
| $c_u$ | The cost of an unplanned stop |
| $I$ | A function which partly determines the insurance premium |
| $L$ | The insurance amount (equal to the individual liability limit) |
| $m$ | The level of maintenance (assuming perfect correlation between $m_r$ and $m_s$) |
| $m_r$ | The amount of maintenance done to improve the reliability and economic performance |
| $m_s$ | The amount of maintenance done to improve the safety performance |
| $m_{s,reg}$ | The minimum level of safety maintenance imposed by regulatory agencies |
| $p$ | The market price of electricity |
| $p(m)$ | The probability of an unplanned stop (assuming perfect correlation between $m_r$ and $m_s$) |
| $p_r(m_r)$ | The probability of an unplanned stop |
| $p_s(m_s)$ | The probability of an unsafe event |
| $q$ | The quantity of electricity produced per unit time |
| $\pi$ | Profit |

# Contents

# 1 Introduction

Some industries or projects are risky in nature and the cost of accidents may be very high for both the owner and for society as a whole. A few examples of such industries are nuclear power, off-shore oil drilling and construction projects in areas susceptible to environmental hazards. The expected return to investment in these industries may be very high but there is a risk of large accidents, with an associated large cost. The probability of accidents can be reduced and the potential consequences can be mitigated by investing in safety measures. These typically reduce the short-run profits but can in some cases increase the long-term profit. Furthermore, certain industries are subject to limited liability, meaning that they are economically liable only up to a certain amount of monetary compensation in case of an accident. This is a sort of indirect subvention by the government to encourage investments in risky industries with high potential benefit for society. However, this limited liability has caused some concerns that the owners of such risky industries will take excessive risks and cause harm to society in order to increase the short-run profits (Shavell, 1982).

This thesis will investigate this concern in the case of nuclear power, which is often a topic of heated debate because of the risk of large accidents—the cost of which may be externalized onto society. Catastrophes like Chernobyl and Fukushima have shown us that it is a real and warranted concern. The clean-up cost of the Fukushima accident has been estimated to reach JPY 20 trillion (about €140 billion) which greatly exceeds both the equity and the assets of the typical nuclear power plant (NPP) owner. This creates a problem of "judgement proof" firms—meaning that firms go bankrupt before they have fully compensated the costs of the accident. The nuclear power industry is therefore heavily regulated in an attempt to (i) create adequate incentives for firms to take a socially optimal amount of risk and (ii) ensure that damages are fully compensated in case of accidents. The task of policy makers is to choose a level of regulation that is optimal for the social welfare. If regulations are too strict, the costs of the NPPs will increase, leading either to a higher electricity price or lower profits so that investors are less likely to invest in projects with high expected return. If regulations are too lax it might lead to an excessive risk-taking, potentially leading to accidents and consequently large costs for society.

Regulations can be divided into two categories—safety regulation (*ex ante*) and liability regulation (*ex post*). The safety regulations are difficult to measure but they have increased over time, especially in response to large accidents such as Three Mile Island and Chernobyl which have highlighted problems in the safety systems. The liability regulation, on the other hand, can easily be quantified. In the U.S., the limited liability has been increased incrementally from $60 million in 1957 to $375 million in 2010.

The theoretical relation between regulations and risk-taking is well developed but there have been few attempts done to show whether policy changes have a real impact on the safety of NPPs. (Rust and Rothwell, 1995) show that the reliability and safety of reactors improved after Three Mile Island in response to increased safety regulations but there have been no empirical studies done to investigate whether limited liability has an effect on nuclear safety. It is therefore of interest to investigate whether the increases in limited liability have had an effect on the risk-taking, and ultimately accident frequency, of NPPs.

## 1.1 Goal

The purpose of this paper is to empirically investigate whether changes in liability regulation affect the risk-taking of nuclear power plants, and thus reduce the risk of nuclear accidents. The empirical investigation will be limited to U.S. nuclear power plants in the 90s and 00s due to data availability and statistical problems for other countries and time intervals.

## 1.2 Present Knowledge

There has been research done on how safety regulation and liability regulation interact and how they affect the risk-taking of firms in hazardous sectors. One strand of the research is primarily based on (Shavell, 1982, 1984, 1986) and it has been further commented upon by (Eberl and Jus, 2012; Kolstad et al., 1990; Schmitz, 2000; Beard, 1990). These papers create a model based on firms' profit maximization of how safety regulations and liability regulations interact, and investigate in which cases the outcome will be optimal from society's point of view. The insights concerning the interaction of safety and liability regulations will be used in this thesis but the model is too simplified for our needs. (Shavell, 1982) models how insurance interacts with limited liability, and while this model provides some qualitative insights, it is not easily transferred into an empirical setting.

A different approach for modelling the risk-taking of NPPs can be found in (Hausman, 2013). She develops a model which, too, is based on profit maximization of firms and uses it to show how divestiture improves the safety performance of NPPs. Hausman also separates economic reliability from safety performance which turns out to be useful for the purpose of this thesis. However, Hausman does not consider insurance in her model so it has to be modified to suit our present needs. This will be the basis of our theoretical framework.

There have been few empirical works in this area. (Ringleb and Wiggins, 1990) show that a relaxation of liability regulations leads to an increase in the number of firms in hazardous sectors. The previously mentioned (Hausman, 2013) empirically investigates the effect of divestiture on safety.

Given this present knowledge, we aim to contribute in three areas:

1. Improving the theoretical model so that it fully incorporates liability insurance.
2. Gathering the relevant dataset
3. Empirically testing whether an increase in the limited liability has an impact on the risk-taking of NPPs.

## 2 Theoretical framework

The following section will describe a causal model of how regulations affect risk-taking and will be the basis for the hypothesis we formulate before beginning the empirical work. The basic set-up concerns how NPPs maximize their expected profits and is based on (Hausman, 2013). We modify the model by including the effect of liability insurance as well as discussing how liability regulations interact with safety regulations. These modifications are qualitatively inspired by the article on liability and insurance in (Shavell, 1982).

### 2.1 The basic profit maximization model

The model will define the NPP owners as actors and will take regulations as exogenous factors imposed upon them by society. The actors are assumed to be rational and well informed and thus maximize their expected operating profit $\pi$ as a function of their produced electricity quantity $q$, the price of electricity $p$ and the variable cost of producing electricity $c_v$.

$$\pi = pq - c_v q \tag{2.1}$$

NPPs are characterized by high capital cost and low variable cost while having high start-up costs after downtime (MIT, 2003). This means that nuclear power can be considered as baseload capacity and that they are price takers since other types of power generation technologies with higher marginal costs will set the price. Given the high capital cost of an NPP, it must be in operation as much as possible for it to create a competitive return on investment. While it would be ideal to run a plant all the time, the equipment of the plant will deteriorate over time, and sooner or later some critical component will break down and cause an unplanned stop. Unplanned stops lead to one, or both, of the following consequences:

1. An economic loss due to lost operating time and potential repairs.
2. Safety hazards to workers or society.

Unplanned stops can be prevented or mitigated by doing regular preventive maintenance to control and replace components before they break, as well as investing in new systems. Maintenance usually requires shutting down the reactor (a planned stop), which is costly due to lost operating time, so excessive maintenance is unprofitable for the NPP. Therefore, in order to maximize profits, there is a trade-off between planned stops for maintenance and the number of unplanned stops.

As mentioned above, there are two types of possible consequences—economic and safety related—and maintenance can be targeted at reducing just one of the two. It is always in a profit maximizing owner's interest to improve the economic performance of the plant but it might not be in the owner's interest to improve the safety performance. It is therefore useful to separate the two type of maintenance in the model. $m_r$ will denote the amount of maintenance which is done to improve the reliability and economic performance of the plant, and $m_s$ will denote the amount of maintenance which is done to improve the safety performance of the plant.

To clarify this distinction, a few examples will be given. Installing an air filter which cleans leaks from the reactor containment is only useful in mitigating serious accidents and has solely a safety function. Installing a faster refuelling mechanism has the function of minimizing the downtime during refuelling and has solely an economic function. However, some maintenance will improve both the economic and safety performance—replacing critical components before they break, for example—so there is a correlation between the two. Since the exact degree of correlation is unknown, we consider the cases with zero correlation and perfect correlation separately in the following section.

### 2.2 Case 1: Zero correlation between economic reliability and safety

First, assume that there is no correlation between reliability and safety maintenance. Doing reliability maintenance incurs a cost $c_r(m_r, \pi)$. We assume that:

$$\frac{\partial c_r}{\partial m_r} \geq 0, \quad \frac{\partial c_r}{\partial \pi} \geq 0, \quad \frac{\partial^2 c_r}{\partial m_r^2} \geq 0$$

meaning that further maintenance will incur further costs, that the marginal cost is increasing, and that higher profits increases the opportunity cost of maintenance. Given a certain level of $m_r$, there is a corresponding probability of unplanned stops $p_r(m_r)$ which will cause the reactor to be shut down, decreasing operating time and incurring an additional cost $c_u$. We assume that $p_r'(m_r) < 0$ and that $p_r''(m_r) > 0$, which means that additional maintenance will decrease the risk of unplanned stops and that the marginal effect is decreasing with increasing maintenance.

Analogous to the previous paragraph, we assume that the safety maintenance $m_s$ has a cost function $c_s(m_s)$ and probability function $p_m(m_s)$ with the same properties as its reliability counterparts.

#### The effect of liability insurance

As previously mentioned, an NPP will choose a level of reliability maintenance which optimizes the economic performance. That is not necessarily the case for safety maintenance since the harm might fall on society rather than the owner. To solve this problem, the cost of accidents is internalized onto the NPP through liability regulation. In the case of nuclear power, all liability regulations are strict, meaning that the liability is not conditional on whether the actor has been acting negligent prior to an accident—the actor will always be held liable to pay for the damages. Furthermore, within the nuclear industry, the liability is limited to a maximal amount. Either it is limited by regulation (*de juro*), or by an actors' equity (*de facto*). In the U.S., liability is currently limited to \$375 million which is much smaller than the cost of a typical large scale accident. In this paper we are interested in large accidents which may affect society and it is therefore reasonable to assume that the cost of accidents exceeds the liability limit.

The NPPs buy insurance to cover the liability rather than keeping cash or cash equivalents. Each country has its own requirements regarding the amount of insurance required of the NPPs. In addition to an individual insurance per reactor, a common insurance pool is set up among the NPPs. The funds from the insurance pool are used to cover the costs that exceed the individual insurance limit. In this model, the effect of the common pool will be ignored since the maximum amount which has to be paid to the pool is a fraction of the individual liability (about one quarter in the U.S.) The effect of the pool's size is therefore negligible compared to the size of the individual liability.

Insurance premiums will generally depend on the insurance amount $L$, the probability of accidents $p_s(m_s)$, and the cost of potential accidents—in short, the expected insurance claims. The premiums are determined by local insurance companies, such as the American Nuclear Insurers. The models they use to set the premiums are not available to the public so some assumptions have to be made concerning the nature of the model. The assumptions made in this theoretical framework are:

1. Premiums are proportional to the insurance amount $L$. The function's exact shape is unknown but for simplicity it is assumed to be linear.
2. Premiums are lowered when the probability of accidents $p_s(m_s)$ decreases.
3. That accidents are so costly that the insurance claim will equal the full insurance amount. This makes the premium independent of the cost of accidents, since the claim will always equal $L$.

Given these assumptions, the insurance premium can be expressed as $I(p_s(m_s))L = I(m_s)L$ (since the probability of accidents $p_s(m_s)$ is a function of the maintenance $m_s$ only), which increases linearly with $L$. The question arises how the function $I(m_s)$ may look. The insurance companies have imperfect information of the safety maintenance and are therefore unable to calculate the exact probability $p_s(m_s)$. Thus they can not set a premium that perfectly matches $m_s$. The premiums can be affected by improving the safety of a plant but not by a very large amount (Pyk, G, 2014). The unsymmetrical information problem makes the relation between premiums and safety maintenance weaker, but we can still assume that $I'(m_s) < 0$ and that $I''(m_s) = 0$.

### The modified profit maximization model

Combining the aspects discussed above we can write the NPP's profit maximizing problem as

$$\max_{m_r, m_s} (1 - p(m_r))\pi - p(m_r)c_u - c_r(m_r, \pi) - c_s(m_s, \pi) - I(m_s)L \tag{2.2}$$

The first term is the profit and the second is the cost of unplanned stops. The third and forth terms are the costs of doing maintenance, and the fifth term is the insurance premium. As compared with (Hausman, 2013), the last term is the modification to the model. Differentiating the equation above gives the first-order conditions

$$-p'(m_r)\pi - p'(m_r)c_u - \frac{\partial c_r(m_r,\pi)}{\partial m_r} = 0 \tag{2.3}$$

$$-I'(m_s)L - \frac{\partial c_s(m_s,\pi)}{\partial m_s} = 0 \tag{2.4}$$

This paper concerns the safety level of NPPs so the second equation is of primary importance. The question of interest is what would happen if $L$ increased from one time period to another. Since $I'(m_s)$ is constant and negative, the marginal cost of safety improvements $\frac{\partial c_s(m_s,\pi)}{\partial m_s}$ must increase. Since the marginal cost increases monotonously with regards to $m_s$, it therefore implies that $m_s$ increases when $L$ increases. The situation is visualized in Figure 2.1.

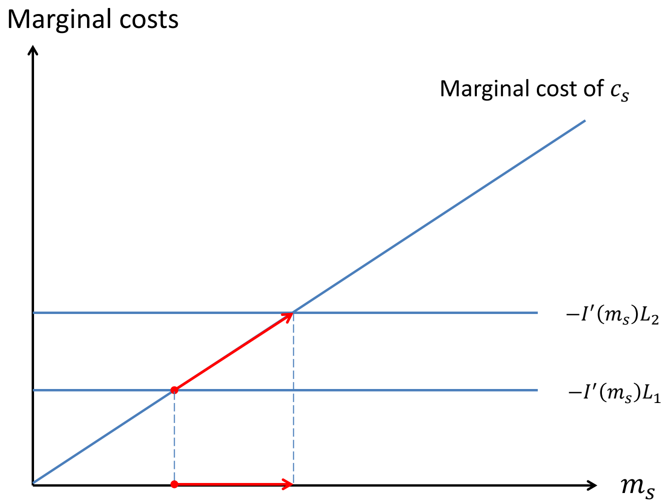


**Figure 2.1:** A graphical representation of how an actor improves the safety maintenance in response to an increase in $L$ under profit-maximization.

As a thought experiment, if insurers are completely unable to observe $m_s$ we would have that $I'(m_s) = 0$ and therefore $\frac{\partial c_s(m_s,\pi)}{\partial m_s} = 0$. This would lead to NPPs choosing $m_s = 0$ as the profit maximizing level of safety-related maintenance.

## 2.3 Case 2: Perfect correlation between economic reliability and safety

With perfect correlation between $m_r$ and $m_s$, we can combine them into one maintenance term $m$. The setup is otherwise analogous to the previous case. That is, there is a probability for unplanned stops $p(m)$ with the properties $p'(m) < 0$ and $p''(m) > 0$. There is also a cost $c(m,\pi)$ of doing maintenance. The maximization problem now becomes:

$$\max_m (1 - p(m))\pi - p(m)c_u - c(m,\pi) - I(m)L \tag{2.5}$$

The first-order condition is:

$$- p'(m)\pi - p'(m)c_u - I'(m)L - \frac{\partial c(m,\pi)}{\partial m} = 0 \tag{2.6}$$

The main difference from Eq. (2.4) is the first two terms, so lets consider what happens as $L$ increases. The first three terms are all positive while the last term is negative. As $L$ increases, the marginal cost of maintenance must therefore increase as well, which in turn implies an increases amount of maintenance. As maintenance increases, the first two terms will decrease, reflecting the diminishing economic return to additional maintenance.

Having considered with zero correlation and perfect correlation between $m_s$ and $m_r$, the qualitative result is the same. It is therefore likely that the model predictions will hold for any degree of correlation between the two extreme cases.

## 2.4 The interaction of liability and safety regulation

The limited liability of NPPs and the problem of insurers' imperfect information decreases the incentives of NPPs to maintain a high safety level. For that reason the industry is heavily regulated and the safety regulations stipulate a minimum level of safety. If a plant fail to reach this minimum safety level and get detected by the regulatory agency the plant will be stopped and the owner fined. This will modify the model above in a simple way. We have already calculated the profit maximizing $m_s$, and if the regulating agency stipulate a minimum safety maintenance level of $m_{s,reg}$, the NPPs will choose

$$\max(m_s, m_{s,reg}) \tag{2.7}$$

This complicates the empirical situation and makes it less clear how the NPPs will react when $L$ increases. If $m_{s,reg}$ is higher than both pre-change and post-change $m_s$, there will be no difference in the safety maintenance. In order to observer a change, it is required that $m_s > m_{s,reg}$. The situation is shown in Figure 2.2

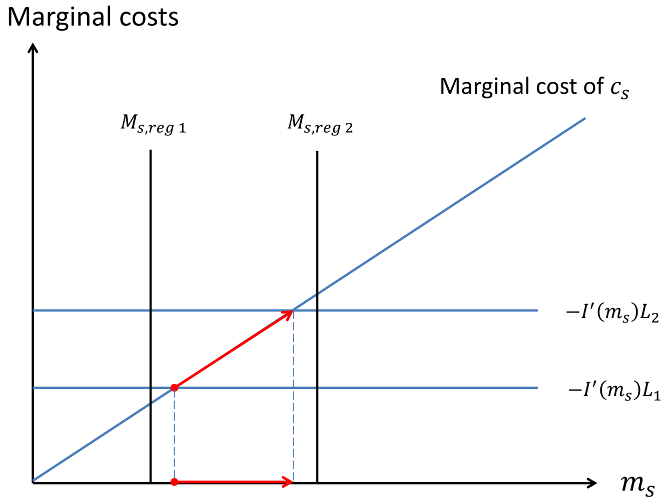


**Figure 2.2:** A graphical representation of how $m_s$ interacts with safety regulation. If safety regulations are $m_{s,reg,1}$ we can observe a change in $m_s$ in response to a change in $L$. If safety regulations are $m_{s,reg,2}$ we can see no such change.

## 2.5 Hypothesis

As mentioned throughout the theoretical framework, we expect to see a positive correlation between the limited liability limit $L$ and the amount of safety-related maintenance $m_s$, and thus a negative correlation with the number of unsafe events. The effect will only arise if the profit maximizing $m_s$ is higher than the $m_{s,reg}$ stipulated by the regulators but it is not possible to *a priori* control whether this holds or not. This will be tested with the regression model (see section 4.1 for a detailed explanation):

$$y_{it} = \beta_1 L + \beta_1 x_{it1} + ... + \beta_n x_{itn} + a_i + u_{it} \tag{2.8}$$

The null and alternative hypotheses can then be formulated as:

$$\mathrm{H}_0\text{: } \beta_1 = 0$$
$$\mathrm{H}_1\text{: } \beta_1 \neq 0$$

# 3 Empirical setup

We have gathered a time series for the 102 U.S. reactors, from 1993 to 2012, for three reasons:

1. Some control variables—which are difficult to quantify—are relatively constant over short time periods within one country while they could vary greatly in a spatial cross section and over longer time periods. In particular, the safety regulations change quickly in response to large accidents such as Three Mile Island and Chernobyl.

2. The U.S. is the country with the largest amount of reactors in the world which improves the chance of achieving statistical significance.

3. In 2003 there was a significant change in the liability regulation and there is reliable safety performance data available both before and after that change.

We are primarily interested in two variables: the liability limit $L$ as the independent variable and the risk-taking (inversely proportional to accident prevention maintenance $m_s$) as the dependent variable. The former is easily quantified, but the latter is difficult to measure, since it includes activities such as personnel training, inspection and maintenance routines, and construction of additional safety systems. These are not measurable so one must therefore find proxy variables which are correlated with risk-taking. The best option is to look at the outcome of risk-taking—that is, the frequency of accidents or other unplanned events that may lead to larger accidents. The number of recorded significant accidents depends on how an accident is defined but even with a generous definition, the number of significant accidents is too small to get statistically significant results and so one must use alternative proxy variables.

## 3.1 Nuclear power plant operational metrics

NPPs regularly report their operation data to various agencies, whom later publish it in annual reports. The operational data is given by a number of metrics which are defined in IAEA's annual report on *Operating Performance with Nuclear Power Stations in Member States* (IAEA, 2012). The metrics will be used both to measure safety performance and control variables.

#### Reference Unit Power (RUP) [MW]

The reference unit power is the maximum (electrical) power that could be maintained continuously throughout a prolonged period of operation.

#### Reference Energy Generation (REG) [MWh]

Net electrical energy which would have been supplied to the grid if the unit were operated continuously at the reference unit power during the whole reference period.

**Energy Loss (EL) [MWh]**

Energy loss is the energy which could have been produced during the reference period by the unavailable capacity; it is categorized into three types:

- PEL - Planned Energy Loss
- UEL - Unplanned Energy Loss
- XEL - Energy loss due to causes external to the plant

**Energy Availability Factor (EAF) [%]**

$$EAF = \frac{REG - PEL - UEL - XEL}{REG} * 100 \tag{3.1}$$

The energy availability factor is the ratio of the energy that the available capacity could have produced during this period, to the energy that the reference unit power could have produced during the same period.

**Unplanned Capability Loss Factor (UCLF) [%]**

$$UCLF = \frac{UEL}{REG} * 100 \tag{3.2}$$

Unplanned capability loss factor is defined as the ratio of the unplanned energy losses during a given period of time, to the reference energy generation, expressed as a percentage. Unplanned energy loss is energy that was not produced during the period because of unplanned shutdowns, outage extensions, or unplanned load reductions due to causes under plant management control. Causes of energy losses are considered to be unplanned if they are not scheduled at least four weeks in advance.

**Planned Unavailability Factor (PUF) [%]**

$$PUF = \frac{PEL}{REG} * 100 \tag{3.3}$$

Planned unavailability factor is defined as the ratio of the planned energy losses during a given period of time, to the reference energy generation, expressed as a percentage.

**External Unavailability Factor (XUF) [%]**

$$XUF = \frac{XEL}{REG} * 100 \tag{3.4}$$

External unavailability factor is defined as the ratio of energy losses due to external factors during a given period of time, to the reference energy generation, expressed as a percentage.

## 3.2 Proxy variables for risk-taking

We have opted to use two different metrics as proxies for risk-taking: Unplanned Capability Loss Factor (UCLF) and radiation exposure of workers. Each of these will be explained in greater detail below.

#### Unplanned Capability Loss Factor

The average annual values of UCLF from 1993-2012 are shown in Figure 3.1. Unplanned stops occur when there is an unforeseen and possibly dangerous event in a reactor, so in order to avoid an event escalation the reactor is shut down. According to (IAEA, 2012), the causes of the outages are divided into several categories. The most common categories which count toward UCLF are:

- Plant equipment failure
- Testing of plant systems or components
- Nuclear regulatory requirements
- Human factor related

Plant equipment failure normally constitutes the majority of the hours lost. Nuclear regulatory requirements are usually enforced by the Nuclear Regulatory Commission (NRC), and they can shut down a plant until it makes the adequate adjustments to meet the safety requirements set by NRC. Unplanned stops related to human factor constitutes a very small fraction of the hours lost.

Furthermore, each time a reactor is shut down or restarted, the risk for an accident increases compared to steady operation. This is especially the case when the stop is unplanned. It is therefore intuitive that the number of unplanned stops and outages should be correlated with the risk of accident escalations in the NPP. As the NPP increases the safety maintenance, the number of unplanned stops should decrease.

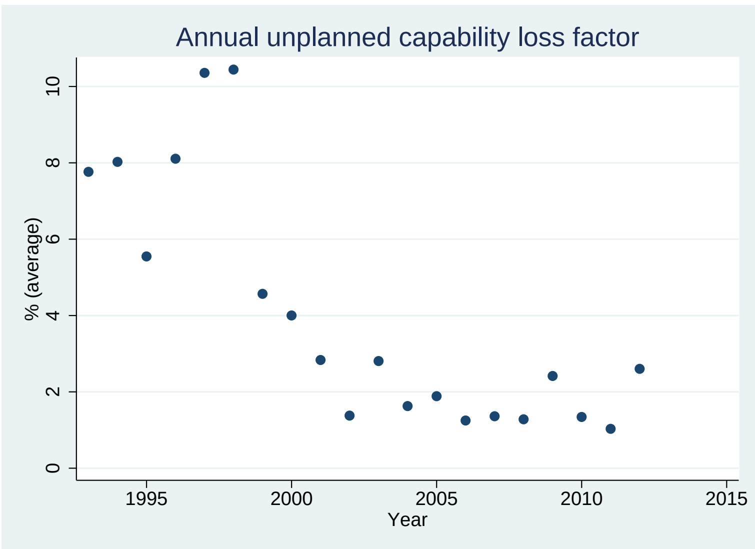


**Figure 3.1:** Average annual Unplanned Capability Loss Factor for 1993-2012.

Looking at Figure 3.1, it would appear that the average values from 1993 to 1998 are much higher compared to the values for later years. One possible reason for this is that there were more NPPs who did not meet the safety requirements set during that period. For example, in 1993, the reactor Browns Ferry-3 was shut down the whole year so that they could resolve various concerns from NRC. Also, in 1996, the reactor Salem-2 received an enforcement action letter from NRC, which resulted in an extended outage of 8040 hours (UCLF = 91.8%).

If the NPPs receive several enforcement actions from the NRC, it would indicate that they do not meet the safety requirements. This means that $m_s < m_{s,reg}$. As discussed in section 2.4, we would like to have $m_s \geq m_{s,reg}$ in order to see an effect upon a change in the liability limit. Because of this, we will drop the years prior to 1999 in the regressions.

The UCLF variable is scaled with EAF plus UCLF since we are interested in the fraction of stops with respect to the time the reactor has been intended to be in operation. The new variable becomes:

$$UCLF_{scaled} = \frac{UCLF}{EAF + UCLF} = \frac{UCLF}{100 - PUF - XUF} \tag{3.5}$$

This means that we should not control directly for PUF in the regressions with UCLF$_{scaled}$ as proxy variable since PUF appears in the denominator of UCLF$_{scaled}$. Therefore, we only control for lagged PUF values, up to 3 years. The unscaled UCLF will not appear again and for brevity $UCLF_{scaled}$ will be referred to as UCLF from this point onwards.

**Worker radiation exposure**

The personnel in NPPs carry dosimeters which measure the radiation dose they receive while on the job. The largest doses are normally received during refuelling and can be reduced by a well-planned plant layout, ample radiation shielding, choice of materials, effective procedures and careful planning of work in the reactor (Pershagen, 1989). As such, it is clearly related to how much the plant owner prioritizes safety and invests in improvements. If an accident happens at a reactor with a relatively high worker radiation exposure—which implies poor radiation shielding, poor procedures and a poor plant design—it is more likely for the accident to have more dire consequences and subsequently a higher social cost.

Values of worker radiation exposure can be found in the NRC report *"Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities"* (NUREG-0713) (Lewis et al., 2013). Data exists from 1974 up to 2011. We use the average worker radiation exposure per reactor.

Figure 3.2 shows the average annual worker radiation based on reactor technology. We can see that there is a systematic difference in the level of radiation dose between BWRs and PWRs. This is also emphasized by (Lewis et al., 2013). This difference is to be expected given the technological differences—in BWRs the steam in the secondary circuit is activated (some molecules in the steam are radioactive) while in PWRs the steam in the secondary circuit is not activated. This causes workers in the BWR's turbine hall to receive larger doses.

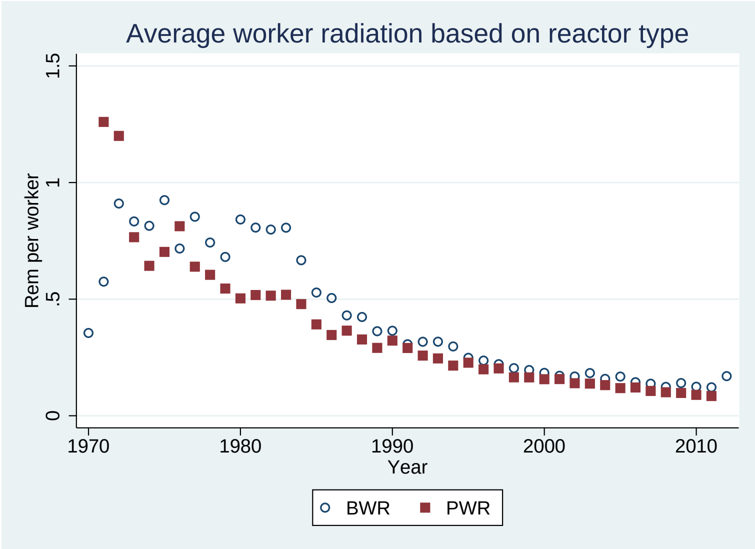


**Figure 3.2:** Average annual worker radiation based on reactor technology.

The level of worker radiation exposure is typically uncorrelated with the UCLF (the correlation is 0.0685 in our dataset). The majority of the radiation is received during planned stops (refuelling) and normal operation, and is thus unrelated to unplanned stops. An accident which causes an unplanned stop may also increase the radiation exposure of a few workers but since we use the average radiation exposure per reactor this will not have a major impact on the measurements. Since the radiation exposure measure is primarily driven by time spent refuelling (as opposed to operating time), it is therefore not scaled.

## 3.3 Variables affecting risk-taking

Below we will describe the independent variables that are relevant for the regression—both the liability limit and the various control variables.

### Liability limits

The United States has a federal law, the Price-Anderson Nuclear Industries Indemnity Act, which regulates the liability of NPPs. The system has three tiers: (i) an individual liability, (ii) a common pool between all U.S. reactors and (iii) the government. The actual numbers have increased over time and since 2010 it requires that all NPP owners have the minimum individual insurance of $375 million per reactor. The contributions to the common insurance pool is set at approximately $120 million per reactor (as of September 2013) which bring the pool to a total of $13.6 billion, which is paid out if the cost of an accident exceeds $375 million (Winston & Strawn LLP, 2013). If the amount exceeds $13.6 billion, the government will pay the remaining cost.

The amount needed for individual liability insurance has increases in several steps over the years (see Figure 3.3). In the first version of the Price-Anderson Act the amount of $60 million and as of today it is $375 million (Winston & Strawn LLP, 2013).

The liability limit change in 1988 was made in connection with a large nuclear accidents which makes it difficult to control for safety regulation changes. The liability limit change in 2010 is not useful since there is not enough data available after the change. We are therefore left with the regulation change in 2003 when the amount went from $200 million to $300 million. It would be statistically better to examine a time period with multiple liability changes—in that case we could use the actual values of the liability limits. However, that would also introduce a greater variation in safety regulations. Therefore, to represent the policy change, we create a dummy variable which is true after the change and false prior to the change.

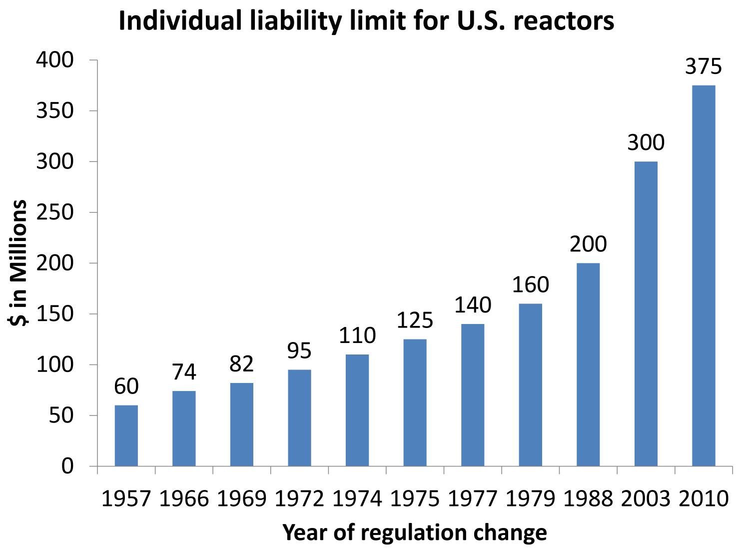


**Figure 3.3:** The levels of the individual liability limit since the Price-Anderson Act was introduced. Data source (Winston & Strawn LLP, 2013).

**Control variables**

Except for the liability limit, there are a number of other factors which also may have an effect on the safety of a plant. The ones which we have identified are:

- The strength of the safety regulations
- The safety culture in the country
- The age of the reactor
- The construction date (or generation) of the reactor
- The power of the reactor
- The reactor technology/type
- Divestiture
- Planned Unavailability Factor

The control variable that is most difficult to control for is the strength of the safety regulation. The spatial variation is eliminated by restricting the data to one country. Safety regulation typically increases in great leaps after significant accidents reveal flaws in the NPPs' safety systems. After the accidents at Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011) there were large efforts made to increase the safety regulations. Otherwise it is improved in small incremental steps over longer time periods. By looking at a time period around 2003 (when the liability regulation change happened), the variation in safety regulations should be kept small and be assumed to be constant. Furthermore, in 1997-1998 the NRC had a major crackdown on several plants which made the UCLF measurements abnormally large during those years (IAEA, 2012). The time period used in our empirical study has been limited to 1999-2010 for this reason.

The technology, power and age of each reactor are easily found and controlled for in the regression. There are only 2 types of reactors in the United States, Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR). BWRs are often considered to be more risky than PWRs and needs to be controlled for. The age of a reactor might have an effect on the safety performance. The Swedish operating experience during the 70s showed that the safety performance improved during the first 10 years after construction since there are many "baby problems" in the reactors during the first years which later get resolved (Pershagen, 1989). Later in the reactor's lifetime it is plausible that it becomes more prone to accidents as the various components get older, creating a U-shaped dependence on the age. It is therefore important to control for the reactor's age in the regression.

It should also be mentioned that the age is correlated with how advanced the reactor technology is since the reactor designs have improved over time. This means that a part of the age effect is due to refinements in design, and not only operating experience, wear of components and similar effects. The designs of modern reactors are safer than the ones built in the 60s. Generation II reactors were built between 1969 and 1996. All of the reactors in our data were built in that time period, which means that the fundamental designs are similar.

The greater the power of the reactor is, the bigger and more complex will the technology be. It is therefore plausible that bigger reactors will be more prone to fail which is supported by Swedish data (Pershagen, 1989). However, it must be noted that the power is correlated with the age since the power of new reactors has increased steadily over time. All the reactor hardware characteristics mentioned can be found in (IAEA, 2012).

The effect of divestiture on nuclear safety is investigated in (Hausman, 2013) who reaches the conclusion that divestiture has a significant effect on nuclear safety. The U.S. nuclear industry has undergone a divestiture process during the time period that we are interested in and it is therefore important to control for it. The dates of divestiture of individual plants can be found in an online appendix to the article by (Davis and Wolfram, 2012) and are summarized in Table 1.

Planned Unavailability Factor (PUF) is important to control for since maintenance will improve the safety reliability and thus decrease the amount of unplanned stops. That is, UCLF

**Table 1:** The number of divested plants each year.

| Divestiture year | Number of divested plants |
|---|---|
| 1999 | 3 |
| 2000 | 10 |
| 2001 | 19 |
| 2002 | 4 |
| 2003 | 2 |
| 2004 | 1 |
| 2005 | 4 |
| 2006 | 1 |
| 2007 | 3 |

is likely inversely proportional to PUF. According to (IAEA, 2012), the causes of the outages are divided into several categories. The categories which count toward PUF are:

1. Refuelling without maintenance
2. Inspection, maintenance or repair combined with refuelling
3. Inspection, maintenance or repair without refuelling
4. Testing of plant systems or components (UCLF also counts toward this category)
5. Major back-fitting, refurbishment or upgrading activities with/without refuelling

We know that sooner or later, a nuclear plant has to schedule a stop in order to refuel. The majority of the unplanned hours are listed under two category (1) and (2): inspection, maintenance or repair with and without refuelling. It is unknown exactly how maintenance is done when it is combined with refuelling and this could mean that the actual time spent on maintenance is less than what the level of PUF would indicate. However, we make the assumption that PUF is an adequate proxy for the level of maintenance.

In Figure 3.4 we can see the average annual levels of PUF from 1993-2012. While we only use the observations up to 2010, it is interesting to see the increase after the Fukushima accident in 2010 which show how plants increase maintenance after nuclear accidents.

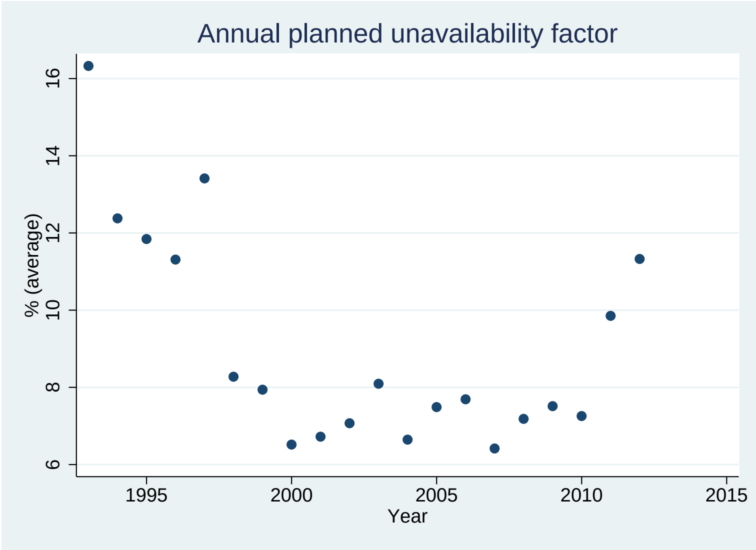


**Figure 3.4:** Average annual Planned Unavailability Factors.

# 4 Results and analysis

## 4.1 Regression model

We will here provide a description and motivation for the regression model that we apply on the data presented above. For each of the dependent variables $y_{it}$ we have the model:

$$y_{it} = \beta_1 L + \beta_1 x_{it1} + ... + \beta_n x_{itn} + a_i + u_{it} \tag{4.1}$$

where $L$ is the liability limit, $x_{it}$ are the control variables, $a_i$ the fixed errors for each reactor and $u_{it}$ a time-varying error for each reactor. The time unit is 1 year. $L$ is represented as a dummy which is 0 up to and including year 2003, and turns 1 in year 2004 and onwards. Since several of the control variables are fixed over time, such as the reactor power, we would like to use a random effects estimator which allows time-invariant independent variables. The main property which decides the choice of estimator is the potential serial correlation of the error term and its correlation with the independent variables. There might be some omitted variables that could cause such a correlation—for example, the reactor designs have been continuously improved over the years and reactors built in the 90s will have more refined safety systems than reactors built in the 60s. It is therefore correlated with the age of the reactor. The strength of the safety regulation, which also has been omitted, increases with time and is also likely correlated with the reactor age. If the errors are indeed correlated with the independent variables, then a random effects estimator would be inconsistent and we would have to use a fixed effects estimator instead. In order to decide between using a random-effects estimator or a fixed-effects estimator, we perform a Hausman test which looks at the correlation between the residuals and the independent variables. Our Hausman test rejects the null hypothesis, which means that the random effects estimator is consistent and more efficient than the fixed effects estimator. We have thus used the random effects estimator for our regressions.

In each NPP, there are usually between one and four reactors. This means that reactors at the same plant share many characteristics such as location, management practices and common safety systems. For example, in 1993 at the plant Sequoyah, reactor unit 1 was shut down to evaluate the piping condition following an extraction steam pipe rupture event on unit 2. The total number of hours lost due to this incident amounted to 7313 hours (UCLF = 83.5%) for unit 1, and 5624 hours (UCLF = 64.2%) for unit 2. We therefore have a correlation between the fixed effects among the reactors within a power plant—a clustering effect. Correcting for clustering in our regressions will give us larger standard errors.

In our dataset, we have dropped the observations for which the Planned Unavailability Factor is larger than 95%. This results in 3 dropped observations. Consider a reactor which has been planned to be stopped for one whole year. Since PUF and UCLF are mutually exclusive (a stop can only be either planned or unplanned), a reactor for which PUF is 100% would automatically result in UCLF being equal to 0%. These occurrences would give us an artificially low UCLF. We could also say that in order to observe accidents, a nuclear reactor has to be running. We also avoid issues with the scaled UCLF by dropping observations where PUF is equal to 100%.

### Control group

When evaluating policy changes it is best practice to compare a test group, which has been affected by the policy, with a control group, which has not been affected by the policy. In this case the policy change affects the whole sample so it is not trivial to find a control group. One promising option is to divide the samples into divested NPPs and non-divested power plants. The logic is that NPPs owned by the state can push increased insurance costs onto taxpayers while private NPPs have greater incentives to optimize their safety and maximize profits. However, the sample size decrease by creating these data subsets (especially the dataset with divested reactors) and the statistical significance suffers.

## 4.2 Results

The regression results below are obtained with the statistics program STATA. Analyses of the residuals show that the random effects method is a good choice for the data.

### Results with UCLF as proxy variable for risk-taking

Table 2 shows the regression results when using UCLF as the proxy variable for risk-taking. The first regression (column 1) includes all the reactors for the time period 1999-2010, with a dummy variable to control for the ownership of the plant. The second regression (column 2) uses a dataset consisting only of NPPs which were divested in 2001 or earlier—prior to the 2003 liability change. The time period for this dataset is limited to 2001-2010 as several of these reactors were public prior to 2001. Finally, the third regression (column 3) is a regression consisting of only non-divested (public) plants for the whole time period 1999-2010.

Here we can see that, for the first and second regression, the liability change in 2003 had a statistically significant effect on UCLF at the 5% and 1% levels respectively. However, the impact of the liability change is insignificant for the third regression. The magnitude of the coefficient is also significantly greater for private NPPs than public NPPs. This means that there is a difference between private and public NPPs when the amount of liability changes. This is also reflected in the divested dummy in regression one. The drop in UCLF is around 1 percentage point in magnitude.

The coefficient for reactor power should be positive or insignificant, since larger reactors are more prone to break down. The coefficient in the first regression is quite significant, although not on the 5% level. The effect is not that large (note that the unit is GW, and the largest difference in reactor power is approximately 1 GW, which means the largest difference between reactors is around 1 percentage point).

When it comes to the remaining variables, there is no significant effect on the level of UCLF.

**Table 2:** Regression results with UCLF as proxy variable for risk-taking.

| | (1) UCLF (all NPPs) | (2) UCLF (private NPPs) | (3) UCLF (public NPPs) |
|---|---|---|---|
| 2003 liability change | -0.00871* | -0.00942** | -0.00202 |
| | (-2.04) | (-2.64) | (-0.49) |
| Age | -0.000904 | 0.00105 | -0.00152 |
| | (-0.73) | (0.64) | (-0.92) |
| $\text{Age}^2$ | 0.0000239 | -0.0000113 | 0.0000285 |
| | (0.92) | (-0.36) | (0.76) |
| Reactor Power [GW] | 0.0120 | -0.00275 | 0.00953 |
| | (0.93) | (-0.16) | (0.71) |
| Reactor type | 0.00182 | -0.000155 | 0.00291 |
| (PWR = 0, BWR = 1) | (0.57) | (-0.04) | (0.66) |
| Divested plant | -0.00782** | | |
| | (-2.94) | | |
| 1-year Lagged PUF | -0.000232 | 0.000114 | -0.000377 |
| | (-1.32) | (0.36) | (-1.72) |
| 2-year Lagged PUF | 0.000349 | 0.0000484 | 0.000117 |
| | (1.35) | (0.15) | (0.58) |
| 3-year Lagged PUF | 0.000252 | 0.0000911 | 0.0000712 |
| | (1.14) | (0.46) | (0.37) |
| Constant | 0.0193 | 0.00325 | 0.0315 |
| | (1.15) | (0.12) | (1.74) |
| Observations | 1003 | 317 | 530 |
| Adjusted $R^2$ | 0.0263 | 0.0479 | 0.0149 |

*t* statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

**Results with radiation as proxy variable for risk-taking**

Table 3 shows the regression results when worker radiation exposure is used as the proxy variable for risk-taking over the time period 1999-2010. Once again, the first column includes all reactors, while the second column only includes NPPs divested in 2001 or earlier, and the third column includes reactors which have been public for the whole time period.

Here we see that the liability change had an impact on the worker radiation exposure at a 0.1% significance level for all reactors. As we divide the dataset, we see that only the public NPPs show a significant coefficient. It should be kept in mind that a typical value for worker radiation exposure is 0.2, so a coefficient of $-0.0207$ means roughly a 10% decrease due to the liability change coefficient.

The PUF coefficient is positive and significant at a 0.1% level for the first and third regression. Reactor type, too is positive and significant at a 0.1% level for the first and third regression. Reactor power has a negative and significant coefficient for the first and third regression. UCLF has no significant effect on worker radiation exposure.

**Table 3:** Regression results with average worker radiation as proxy variable for risk-taking.

| | (1)<br>Radiation (all NPPs) | (2)<br>Radiation (private NPPs) | (3)<br>Radiation (public NPPs) |
|---|---|---|---|
| 2003 liability change | -0.0207*** | -0.0190 | -0.0260*** |
| | (-3.61) | (-1.42) | (-4.49) |
| Age | -0.00122 | 0.00184 | 0.00107 |
| | (-0.61) | (0.24) | (0.44) |
| Age$^2$ | -0.0000379 | -0.000119 | -0.0000652 |
| | (-1.11) | (-0.94) | (-1.45) |
| Reactor Power [GW] | -0.0954*** | -0.136 | -0.0946*** |
| | (-4.70) | (-1.91) | (-3.84) |
| Reactor type | 0.0380*** | 0.0281 | 0.0310** |
| (PWR = 0, BWR = 1) | (3.81) | (0.91) | (3.21) |
| Divested plant | 0.00461 | | |
| | (0.61) | | |
| PUF | 0.00241*** | 0.00154* | 0.00242*** |
| | (7.85) | (2.45) | (6.56) |
| UCLF | 0.000831 | 0.00170 | 0.000641 |
| | (1.83) | (0.66) | (0.95) |
| Constant | 0.263*** | 0.309 | 0.222*** |
| | (6.35) | (1.72) | (4.45) |
| Observations | 1313 | 320 | 693 |
| Adjusted $R^2$ | 0.1962 | 0.1026 | 0.3053 |

*t* statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

### 4.3 Discussion

We have represented the liability change with a dummy which is 0 up to and including 2003, and turns 1 from 2004 and onwards. This means that the coefficient really represents any change that was made in 2003—not only the liability change. To the best of our knowledge there were no other significant external shocks in 2003 which would have affected the safety performance, but a steady time trend could be partly absorbed into the coefficient. In Figure 3.2, we can see that there is a clear trend for how the level of radiation changes over time, while we can see in Figure 3.1 that there is no clear trend for UCLF within the time period 1999-2010.

One possibly important control variable which is not included in this regression is the effect of public opinion. A poor public opinion of nuclear power might force the NPPs to stop operations (see Germany after the Fukushima accident) so it is important for the NPPs to appear credible in the eyes of the public. Public opinion usually change drastically after accidents while changing rather slowly at other time. Leaving out this variable might cause an omitted variable bias in the regressions and it would be interesting to use a measure of public opinion as a control variable in future works.

In Table 2 we see that no control variables, except for divestiture, has a significant effect on UCLF. Given the theoretical framework, we would have expected PUF to have a negative coefficient since more maintenance should decrease unplanned stop. A possible explanation for the unpredicted result is that the value of PUF is determined by factors other than the amount of maintenance. If the length of a planned stop is determined by the refuelling rather than the amount of maintenance (contrary to our assumption), there will be no clear relation between PUF and UCLF.

In Table 3 we can see that the control variables for radiation exposure largely confirm what was known prior to the regression. The main part of the radiation dose is received during refuelling and maintenance so it is natural that PUF has a positive coefficient. We also predicted that BWR reactors would have a positive coefficient as well. The reactor power coefficient was not predicted *a priori* but the most plausible explanation is that the reactor size has increased over time so that the larger reactors have improved safety systems compared with the smaller and older reactors.

When dividing the reactors into divested and non-divested dataset, we see that the divested NPPs are more affected by the liability change than non-divested NPPs when using UCLF as the proxy. Vice versa, non-divested NPPs are more affected than divested NPPs when using worker radiation exposure as the proxy. One plausible explanation is that UCLF is related to decreased operating profits so there are important economic benefits in minimizing UCLF, while worker radiation exposure primarily has a safety and health impact for society. The cost of health issues falls largely on society, so the owner of a public NPPs would have greater incentives to improve worker health since the owner ultimately pays the medicals costs as well. Private NPPs can externalize those medical costs and have less incentive to decrease worker radiation exposure.

Looking at the liability change from a perspective of profit maximization, it is reasonable that private NPPs are more concerned about profit. By improving the UCLF of a plant, the operator can mitigate the risk for accidents and decrease the downtime, thus improving operating profits. The theoretical framework predicted this might come at the cost of increased downtime for reliability maintenance (increase in PUF) but it is not supported by the data. On average, divested plants have a 0.78 percentage points lower UCLF. In other words, divested plants are operating 683.28 hours longer on average each year. The average reference unit power for our estimation sample is 0.95 GW, which corresponds to an additional 649 million kWh electricity produced. If we assume that the price of 1 kWh is 10 cents, then the additional revenue is 65 million dollars—showing that even small differences in UCLF has large economic impacts.

The model further predicts that any effect of the liability regulation might be hidden due to a high level of safety regulations, and that the safety regulations are approximately constant over the time period 1999-2010. The regressions show a significant effect of liability regulations which implies that the effect is not hidden by safety regulation. However, an alternative explanation is that the assumption about constant safety regulations is false. If it increases slowly over the time period, while being high enough to determine the safety level, the regressions might be showing the increases in safety regulations rather than liability regulations. Given the difficulty in measuring safety regulations, it is not possible to determine which explanation is the true one with the present dataset.

In the introduction it was mentioned that liability regulations have two purposes: (i) creating incentives to improve safety and (ii) fully compensate accidents that do happen. It could be discussed whether the increase in liability limit over the years have been intended to raise the level of maintenance or if the limit is solely meant to improve the accident compensation to society, or if the limit is increased to gain political favour. In Sweden the main motivation in increasing the liability limit is related to (ii), but the reasoning may vary across countries (Pyk, G, 2014). However, even if the intention is not related to providing incentives to increase the safety level, that might be a consequence of the regulation.

# 5 Conclusions

We set out to investigate whether liability regulations have an impact on the safety performance of nuclear power plants, which is predicted to occur under certain assumptions. Given these assumptions, the results show that liability regulations might have a significant effect on the safety performance. However, the assumptions might be false and it is possible to create plausible stories in which the results show something other than the effect of liability regulations. In order to improve the credibility of the results, the dataset would have to be improved. By using a longer time period, or including more countries, would mean a greater variation in the variables, and it would be possible to estimate the quantitative effect of the liability limit. It is also possible to investigate similar industries which have the same issues with large scale accidents, such as oil drilling. However, such an expansion of the dataset would require additional control variables and that data might be difficult to obtain—most notably the strength of the safety regulation.

This result is in line with the previously mentioned papers (Shavell, 1982, 1984, 1986; Ringleb and Wiggins, 1990). However, it does not appear that liability regulation is a significant driver of nuclear safety—its purpose is rather to compensate accidents and any safety improving incentives should be seen as advantageous, yet small, side effect. For it to have a more significant impact on safety, the insurance premiums would have to be greater than they currently are, and also clearly depend on safety investments so that nuclear power plants can manipulate the insurance premium they have to pay.

To summarize, this thesis' contributions to the field have been to modify a theoretical framework to incorporate insurances, collecting the relevant dataset, and investigating the relationship between liability regulations and safety performance empirically—showing that increasing liability limits plausibly decrease risk-taking of nuclear power plants.

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