Some Unintended Fallout from Defense Policy: Measuring the Effect of Atmospheric Nuclear Testing on American Mortality Patterns

Keith Meyers
University of Arizona [*]

Current Version

October 24, 2017

Abstract

During the Cold War the United States detonated hundreds of atomic weapons at the Nevada Test Site. Many of these nuclear tests were conducted above ground and released tremendous amounts of radioactive pollution into the environment. This paper combines a novel dataset measuring annual county level fallout patterns for the continental U.S. with vital statistics records. I find that fallout from nuclear testing led to persistent and substantial increases in overall mortality for large portions of the country. The cumulative number of excess deaths attributable to these tests is comparable to the bombings of Hiroshima and Nagasaki.

JEL Codes: I10; N32; Q50. Keywords: Nuclear Testing, Public Health, Radioactive Fallout, Defense Policy

---

[*] Meyers, Keith. 1000 E Water Street #5, Tucson, AZ 85719; Economics Dept. Fax: 520.621.8450, Phone: 937-570-0782; Email: meyersk@email.arizona.edu. Manuscript word count: 8,440. This material is based in part upon work supported by the National Science Foundation under Grant Number SES 1658749. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. Thanks to Price Fishback, Derek Lemoine, Ashley Langer, Joesph Ferrie, Jessamyn Schaller, Gary Solon, and Cihan Artunc for feedback, data and support. Additional thanks to Andre Bouville, Steven Simon and the National Cancer Institute for their help providing fallout deposition records.

Pollution is often the byproduct of human activity and imposes significant costs upon the public. In many settings, the government attempts to address the external costs associated with polluting activities, but there are cases where government policy is the direct cause of harmful pollution. During the Cold War the United States detonated hundreds of nuclear weapons just northwest of Las Vegas at the Nevada Test Site (NTS). Prior to 1963 many of these tests were conducted above ground and released tremendous quantities of radioactive material into the environment. One estimate places the total atmospheric release of radioactive material from the NTS as over 12 Billion Curies between 1951 and 1963. In comparison, Chernobyl released an estimated 81 Million Curies of radioactive material (LeBaron, 1998). These nuclear tests exposed millions of Americans to harmful radioactive material and many people are still living with the consequences of this pollution today. This paper measures the effect of domestic atmospheric nuclear testing on the crude death rate for the entire continental United States. I present evidence that nuclear testing had broad and adverse effects on human capital in the extreme and contributed to at least as many deaths as the bombings of Hiroshima and Nagasaki.

The medical and scientific literature studying the health effects of nuclear testing has focused primarily upon small samples of populations who lived in the areas surrounding the Nevada Test Site.[1] These studies examine the health effects of fallout exposure in these populations and extrapolate out the potential health consequences for the nation. Simon and Bouville (2015) of the National Cancer Institute (NCI) note that there is great uncertainly underlying these estimates. They estimate that fallout from domestic nuclear testing caused 49,000 thyroid cancer deaths.[2] One of the major drawbacks of these medical and scientific studies is that they fail to capture the temporal and geographic scope of these health effects.

---

[1] The region surrounding the NTS is termed Downwind in the literature and this area consists of the few counties in AZ, NV, and UT surrounding the test sight.

[2] The 95 percent confidence interval for this estimate is 11,300 and 220,000 deaths. Simon and Bouville (2015) suggest testing contributed up to 11,1000 additional of other cancer deaths. Without nuclear testing they estimated that 400,000 cases of thyroid cancer would arise naturally in the same population.

Using an alternative empirical approach, this paper provides substantial evidence that nuclear testing had profound effects on American health. I combine measures of radioactive fallout exposure from National Cancer Institute (1997) and mortality data for the continental U.S. to analyze the mortality effects of atmospheric nuclear testing. By using within county variation in fallout deposition across years, this paper measures both the geographic and temporal extent of the harm caused by nuclear testing. The results from the empirical analysis reveal that nuclear testing led to prolonged increases in the crude death rate in many regions of the country. Contrary to the assumptions made in the medical literature, the largest mortality effects occurred in the Great Plains and Central Northwest U.S., far outside of the areas studied by the current literature. Back-of-the-envelope estimates suggest that fallout from nuclear testing contributed between 340,000 to 460,000 excess deaths from 1951 to 1973.

Economists have extensively studied the effects of air pollution, lead contamination, and other pollutants upon mortality and public health, but little economic research has studied the public health consequences of atmospheric nuclear testing.[3] The economic research studying the social costs and consequences of radioactive pollution has focused primarily on Scandinavian and Ukrainian populations. Danzer and Danzer (2016) and Lehmann and Wadsworth (2011) study the cost of the Chernobyl disaster to Ukrainian populations using cross sectional variation in exposure. Another body of research has successfully used variation in multiple sources of air pollution as a shock to test the fetal origins hypothesis (Almond et al., 2009a; Almond and Currie, 2011; Currie, 2013; Currie et al., 2015; Isen et al., 2017). With respect to radioactive pollution, both Almond et al. (2009b) and Black et al. (2013) use radioactive pollution to test the fetal origins hypothesis in Scandinavia. Almond

---

[3] Work by Hanlon (2015) has shown that coal consumption in 19th Century England had substantial effects on mortality rates and that coal utilization. Barreca et al. (2014) and Clay et al. (2016) study the long-term health consequences of using coal for heating and electricity generation for the United States. Troesken (2008) and Clay et al. (2014) study how historic municipal decisions relating to the adoption of lead water pipes had long run effects on public health.

et al. (2009b) use radioactive fallout from the Chernobyl disaster and associate negative educational outcomes with in-utero exposure to fallout in Swedish cohorts. Black et al. (2013) use data from 14 radiation monitoring stations in Norway to study exposure in cohorts born between 1956 and 1966. They discover persistent and statistically reductions in educational attainment, earnings, and IQ scores among cohorts exposed during months three and four of gestation.

The results of this paper corroborate the negative effects found in previous research and improves upon the identification by exploiting the specific biological mechanisms through which American populations were exposed to harmful radioactive toxins. Radioactive fallout deposition can be an imprecise measure of human exposure to harmful ionizing radiation. Humans only metabolize specific radioactive isotopes created through fission. The primary mechanism through which people were exposed to concentrated doses of radiation was through the ingestion irradiated food products. Fallout deposition may approximate the presence of fallout in the local food supply, but radiation exposure proxied through deposition becomes more inaccurate if local deposition fails to enter the local food supply. The National Cancer Institute (1997) finds that the consumption of irradiated dairy products served as the primary vector through which Americans ingested large concentrations of radioactive material. During the 1950's most milk was consumed in the local area it was produced. It is through this channel where local fallout deposition would enter the local food supply (National Cancer Institute, 1997). This paper leverages estimates of I-131 concentrations in locally produced milk to provide a more precise estimate of human exposure to fallout than previous studies.

1 Medical, Scientific, and Historical Background

1.1 History of NTS

In the 1950's, millions of Americans were unknowingly exposed to radioactive fallout through both the environment and the food supply. With respect to economic and demographic activities, exposure to radioactive matter from atmospheric nuclear testing can generally be considered as a plausibly exogenous event. Radioactive pollution is often an invisible and imperceptible threat to human health. National security concerns in the 1950's motivated atomic testing at the NTS. While the location of the base was not random, the base was not chosen due to surrounding characteristics of the residing population.[4]

Atmospheric atomic testing on U.S. soil was a deliberate policy decision made by domestic political leaders. In 1949 the Soviet Union detonated its first nuclear bomb Joe-1. Provoked and surprised by this sudden event, U.S. political and military leaders sought to accelerate America's own nuclear weapons program. Prior to this event, nuclear testing occurred in the Pacific.[5] The Pacific tests proved logistically costly, slow to implement, and expensive. American leaders sought a convenient testing location and settled on the Nevada Test Site due to its proximity to U.S. government labs, low levels of precipitation, and relatively secluded location (Center for Disease Control, 2006; National Cancer Institute, 1997). Located in Nye County, Nevada, this military zone became the epicenter of the American nuclear weapons program. Nuclear testing occurred from 1951 until 1992. The period of atmospheric nuclear testing occurring between 1951 and 1963. During this period, the U.S. detonated 100 atmospheric bombs at the NTS (US Department of Energy, 2000).

---

[4] The base was chosen over more environmentally friendly locations due to its proximity to government labs, access to public land, and rapid ease of establishment (Schwartz, 2011).

[5] The three Trinity test in 1945 were conducted in White Plains New Mexico. All other tests conducted prior to the opening of the NTS occurred in the Pacific.

During the 1950's, the public was largely unaware of the dangers that the NTS posed to public health. Often, the Public Health Service (PHS) and Atomic Energy Commission (AEC) sought to dismiss fears regarding the atomic testing. Official government statements made during the testing period asserted that all dangerous radioactive material remained within the confines of the NTS.[6] At best, these organizations failed to adequately warn civilians living around the test site of the health risks associated with these atomic tests (Ball, 1986; Fradkin, 2004; LeBaron, 1998). In 1978, the plight of populations living near the NTS received national media attention. Subsequent Freedom of Information Act requests later revealed that the government knew of these dangers to public health the NTS tests posed and that the AEC had suppressed medical studies highlighting the health dangers (Fradkin, 2004).

1.2 The Health Consequences of Radiation Exposure

Radioactivity generally refers to dangerous particles given off by radioactive decay of matter. The weakest forms of ionizing radiation are alpha particles, and these particles generally cannot penetrate most thin physical barriers. Beta radiation is more dangerous and can penetrate deep into flesh and cause damage. Gamma radiation is the most dangerous form of radioactivity and consists of highly energetic photons. Gamma radiation can travel easily through the body and causes immense damage to biological tissues.

With regards to nuclear testing, there are three radioactive isotopes of concern to human health because of their relative radioactivity, prevalence, and how they are metabolized. These isotopes are Iodine-131, Strontium-90, and Cesium-137. Other isotopes created during nuclear fission are less dangerous to human health because they do not remain in the body for

---

[6] In the Appendix is an example of a 1951 AEC flyer explicitly iterating this official claim. The website for the Official Department of Energy Nuclear Testing Archive where this flyer is from is https://www.nnss.gov/pages/resources/NuclearTestingArchive.html. The government circulated flyers such as these in the areas surrounding the NTS, all while the AEC and PHS detected substantial quantities of fallout depositing in populated areas far beyond the confines of the atomic test range.

extended periods or because they are created in minuscule quantities. Many other radioactive isotopes pass through the body and are secreted following ingestion. In particular, Iodine 131 is a potent radioactive poison. It possesses an eight day half-life, concentrates in the thyroid gland, and emits highly active forms of beta and gamma radiation as it decays (LeBaron, 1998). These traits of I-131 cause acute and rapid damage to tissue surrounding the thyroid. Strontium 90 also appears in wheat and plant products in limited quantities. This isotope collects in bones and teeth. It decays over a long period and causes prolonged damage. Sr-90 possesses a 25 year half-life, diffuses across the body uniformly and emits beta radiation (LeBaron, 1998). Finally, Cs-137, which was released in large quantities during the recent Fukushima Daiichi disaster, collects in fleshy tissue and does not concentrate in any particular organ. It has a half-life of 33 years and emits both alpha and beta radiation (LeBaron, 1998).

The medical and scientific knowledge regarding the effects of human exposure to ionizing radiation comes from many sources. Studies of Japanese atomic bomb survivors and persons living downwind of nuclear test sites provide much of this knowledge. In human population studies of radiation exposure, researchers have measured a variety of negative health and developmental consequences from exposure to ionizing radiation. Studies of atomic bomb survivors and persons exposed during pregnancy demonstrate increased cancer risks, negative developmental and cognitive effects due to radiation exposure (Lee, 1999; Otake et al., 1993; Otake, 1996; Schull, 1997). Researchers studying Chernobyl have found greater incidences of thyroid cancers, and lesions indicative of I-131 poisoning in exposed population (Shibata et al., 2001; Williams, 2002). Researchers studying downwind American populations have also found evidence of increased thyroid cancer and leukemia risks in domestic downwind cohorts (Gilbert et al., 2010; Kerber et al., 1993; Stevens et al., 1990). Together, the medical and scientific literature suggest that exposure to ionizing radiation increases the risks of various types of cancer and can have detrimental effects upon human growth and development. An additional effect of fallout exposure is that it could degrade health, inhibit immune responses, and cause people to die from other non-cancer related causes.

1.3 Exposure Mechanisms

Exposure to harmful radioactive fallout can occur either through direct channels or indirect channels. Radioactive material can enter the body if it lands on the skin with radioactive dust. Many people and animals living in the downwind counties surrounding the NTS were exposed to harmful fallout in this matter. People can inhale radioactive material when it is suspended in the air. Inhalation of radioactive dust would be the most likely in the downwind region. Research by the National Cancer Institute (1997) and Center for Disease Control (2006) establishes that the food supply served as the main indirect vector of exposure for most Americans during the atomic testing period. Scientific evidence contemporaneous with the testing period also substantiates that radioactive materials resulting from nuclear fission appeared in crops, people, and animals (Beierwaltes et al., 1960; Garner, 1963; Kulp et al., 1958; Olson, 1962; Van Middlesworth, 1956). Similarly, the PHS also released research corroborating this evidence but downplayed the health risks associated with the radiation levels reported (Flemming, 1959, 1960; Wolff, 1957, 1959). These government studies often downplayed the risk associated with the levels of radioactive material found in independent studies as alarmist.

The NCI establishes the dairy channel as a primary vector through which Americans were exposed to significant quantities of radioactive material. Most Americans would not be exposed to radioactive dust carried by low altitude winds. Instead, high altitude winds would carry the material far from the test site and the material would only deposit on the ground if it happened to be precipitating while the radiation cloud was overhead. In the few days following the nuclear test, this radioactive material would deposit on crops and pasture.

Some radioactive material would enter wheat and other plant products, but consumption of these products would not necessarily be in the same region where they were produced. Dairy, however, during the 1950s and 1960s was generally produced and consumed locally (National Cancer Institute, 1997). During the 1950s most milk was produced near population centers and delivered daily. In the late 1950s refrigerated truck adoption spread and deliveries switched to every few days (Dreicer et al., 1990). The dairy channel is unique in that cows would consume large quantities of irradiated pasture and concentrate radioactive material, specifically I-131, in milk.

People living in the region where deposition occurred would then be more likely to consume this irradiated food product containing a potent radioactive poison in the days following the atomic test. Pasturing practices would affect the quantities of fallout entering the dairy supply. The areas surrounding the NTS experienced the greatest quantities of radioactive fallout deposition, but often had very little I-131 entering the dairy supply. Dairy farming practices in much of AZ, NV, and UT in the 1950s relied on importing hay from outside regions and as such very little radioactive matter would enter the food supply. This in turn makes deposition itself a less accurate proxy for human exposure to fallout in these areas.

2 Empirical Strategy: Measuring Short Term and Long Term Mortality Effects

2.1 Empirical Model

The empirical analysis of this paper focuses on two different panel regression models to ascertain the geographic and temporal extent of the health cost of atomic testing. The first set of regressions test whether within county variation in radioactive fallout exposure across years had an immediate effect upon crude death rates using a distributed lag framework.

Short run changes in the crude death rate from fallout exposure are potentially less vulnerable to measurement error in treatment and migration bias than regressions measuring the long run effects of fallout. These regressions, however do not fully capture the temporal extent of these increases in mortality rates. The negative health effects of radiation poisoning often materialize long after the damage has occurred. A set of long run regressions employ a distributed lagged framework and pool exposure into five year averages. Estimation of this model measures how persistent the effects of fallout were on crude death rates, accounts for the cumulative effect of fallout exposure over multiple years, and whether exposure to fallout led to harvesting. If exposure to radioactive fallout shortened lifespans and exposed populations who died tended to die at younger ages than if they were not exposed, then these people would not appear in subsequent years in the county panel. This harvesting effect would decrease estimated mortality rates many years following the initial exposure event, because people who would have died in these periods died earlier in the sample.

$$y_{it} = \Sigma_{k=0}^{5} \beta_k * X_{it-k} + \alpha_i + \gamma_{st} + \epsilon_{it} \tag{1}$$

Equation (1) describes the full model specification of this paper. This model tests whether radioactive fallout in locally produced milk or in the environment had a statistically significant effect upon mortality in the years directly following the test. The outcome denoted by y_{it} measures the number of total deaths per 10,000 people in a given county i and year t. X_{it-k} denotes the exposure variable used to proxy for fallout exposure. There are two different measures of radiation exposure used in the analysis. These measures are ground deposition of I-131 and I-131 concentrations on locally produced milk. The variable $Deposition\ Exposure_{it}$ denotes the cumulative measure of total radioactive iodine deposited per square meter in each county year.[7]

---

[7] Alternative functional forms find similar results. These alternative specifications are reported in the online appendix.

The variable $Milk\ Exposure_{it}$ denotes the measure of radioactive iodine in locally produced milk in each county year in thousands of nCi per day/Liter. The NCI created daily integrated estimates of secreted iodine per liter of milk for each nuclear test. They then summed up these secretions over the entire test series. If a cow in a county produced one liter of milk each day, this would measure the amount of radioactive iodine secreted in all those liters of milk in each year. Furthermore, the milk variable accounts for grazing practices across regions. Cows in upstate New York would not have been exposed to much radiation from February tests as they would have been inside barns consuming fodder while cows in Georgia or Texas would have been exposed.

The variables α_i and γ_{st} denote county and state-by-year fixed effects. These county fixed effects control for time invariant county characteristics. The state-by-year fixed effects account for unobserved annual shocks shared across counties within the same state and year. One drawback of state-by-year fixed effects is that they might control for much of the effect of radioactive fallout exposure. Only variation in fallout exposure between counties within the same state provide identification.[8] Alternative specifications replace these state-by-year fixed effects with year fixed effects and state specific time trends to control for possible underlying trends in the data that might be correlated with the exogenous variable of interest. The variable ϵ_{it} denotes the heteroskedastic error term and is clustered at the county level.[9]

$$y_{it} = \Sigma_{j=0}^{5} \theta_j * Avg\_X_{it,j} + \alpha_i + \gamma_{st} + \epsilon_{it} \tag{2}$$

---

[8] Only variation in county level exposure above or below the state year average for exposure provides identification. It is quite likely that the effect of fallout exposure will be underestimated when using state-by-year fixed effects, since the identifying variation is narrower.

[9] Multiple yearly lag structures were tried and the results are generally robust with respect to the number of lags. A specification with five lags was selected since the long run specifications use five year averages. Using five year lags identifies the mortality effect of fallout exposure that is being averaged in the long run panel.

Equation (2) describes the distributed lag specification for the long run panel regressions. This model uses a similar framework to that of Equation 1, but the exposure of interest consists of lagged five year averages of the I-131 exposure measures. The variable $Avg\_X_{it,j}$ denotes the average exposure term with j lags. This distributed lag structure measures the dynamic mortality response to county level radiation exposure over a longer time horizon. Fallout in the current year is excluded from the regression and only past deposition patterns provide variation. This model uses variation in average fallout exposure one to five years prior, six to ten years prior, eleven to fifteen years prior, sixteen to twenty years prior, and twenty-one to twenty-five years prior to identify the temporal extent to which fallout affected mortality patterns.

2.2 Identification and Sample

The source of identifying variation in the empirical analysis comes from within county variation in radiation exposure across years after controlling for state specific annual shocks. There are two main assumptions that allow for measurement of the causal effect of fallout upon mortality. The first assumption is that the exposure variable is orthogonal to the unobserved error term. The second assumption is that most people who were exposed to radioactive fallout eventually die in the county where they were exposed.

Fallout exposure from nuclear testing is a plausibly exogenous event. First, the public generally cannot observe whether they are exposed to radioactive pollution. Radioactive threats generally are imperceptible. Second, the public generally did not know about the polluting effects of the NTS until long after atmospheric testing was suspended. The imprecise public knowledge regarding the effects of fallout exposure prior to 1978 suggests such behavior would be unlikely for much of the country. One challenge to the orthogonality assumption is that people living in the counties surrounding the NTS could observe radioactive dust blows from atomic tests and might have engaged in avoidance behaviors. In order to avoid these potential endogeneity issues, I exclude the counties surrounding the NTS and those counties listed as Downwind by the US Department of Justice (2016) from the empirical analysis.[10] Outside of these counties, people would have been exposed to fallout through the irradiated food supply and not by visible radioactive dust blows.

The second assumption is necessary to measure the treatment effect of fallout upon mortality patterns. Since exposure is at the county level rather than individual level, identification relies on people dying in the counties where exposure is reported. In and out migration would introduce measurement error in the treatment variable. If migration decisions are not systematically correlated with radiation exposure, then migration bias should attenuate the effect of radiation exposure on mortality as the time between the exposure event and reported deaths widen.

2.3 Public Health Data

The empirical analysis uses a county-level annual panel constructed by Bailey et al. (2016) of crude deaths from 1915 to 2007 from Annual Reports of the U.S. Vital Statistics. A subsample from 1940 to 1988 forms the panel for the bulk of the empirical analysis and is selected for its completeness of county level coverage. This panel is used to measure the geographic and temporal extent to which radioactive pollution from the NTS harmed human health. The crude death rate per 10,000 individuals approximates the total mortality effect associated with fallout exposure. Exposure to ionizing radiation can increase cancer risks, but exposure might also make persons less healthy overall and increase non-cancer related mortality rates.

---

[10] A total of 26 counties are excluded from the analysis. These counties are all located in AZ, CA, NV, and UT. Relatively speaking, very few individuals resided in these counties during the testing period and these areas experienced large quantities of fallout deposition. Including these counties into the sample does not substantially affect the estimates using milk exposure but substantially affects the precision of the deposition measures. Including an interaction term for these counties or taking the log of the treatment variable corrects for the imprecision these counties introduce for the deposition measure.

2.4 Fallout Exposure Data

In 1983, Congress authorized the Secretary of Health and Human Services to investigate and measure thyroid doses from I-131 in American citizens. The NCI undertook the task of gathering radiation monitoring station data from historical records. With these records and weather station data the NCI could track the position of the radiation cloud, determine how much radiation would deposit with precipitation, and employ kriging techniques to estimate fallout deposition in counties without monitoring stations. Much of the raw data came from national monitoring stations whose number varied across time, but never exceeded 100 stations. The military also engaged in air monitoring and used city-county stations around the NTS to track the radiation cloud National Cancer Institute (1997).[11] These are the most complete and comprehensive measures for fallout deposition from nuclear tests for the United States. The data employed in this paper are derived from the NCI estimates. The NCI provides estimate for I-131 deposition for each nuclear test conducted from 1951 to 1958, except for three tests in the Ranger 1951 series.[12] The depositions are measured as nanoCuries (nCi) per meter squared and are reported for each day following a nuclear test until the next subsequent test in the series. Figure 1 provides a map of my deposition data for the Upshot Knothole test series. This map show how geographically extensive and heterogeneous fallout patterns are across the country. Notice how states such as Vermont and New Jersey experienced large depositions in 1953.

The NCI also provides daily integrated estimates for I-131 secreted in locally produced milk. These measures are a function of how cows metabolize and secrete iodine at different levels of exposure, grazing practices during the testing window, and the levels of radiation deposition estimated in the kriging model. This methodology can cause substantial differences

---

[11] The locations of monitoring stations is not available through National Cancer Institute records.

[12] The National Cancer Institute is currently trying to create estimates for deposition using simulation methods since monitoring station data is missing for the first three Ranger tests. These tests are not included in this paper's analysis.

between radiation presence in milk estimated at the county level and deposition. During the 1950's, many households consumed locally produced dairy, and I-131's short eight-day half-life means that persons would consume it before the radioactive I-131 would decay. Children would be especially vulnerable to this radiation exposure channel because they tended to drink more milk than adults, had smaller thyroids, and were still growing during this period (National Cancer Institute, 1997). Since a child's thyroid is smaller than an adult's, the same quantity of I-131 would cause greater damage because it would be concentrated into a smaller area. Furthermore, the thyroid regulates growth and development. Harm to this organ might lead to unanticipated long term health problems. Figure 2 provides a map of my milk exposure data for the Upshot Knothole test series.[13] Notice how milk measures vary from the deposition measures. Areas with the highest levels of ground deposition around the NTS have relatively low levels of I-131 present in the local milk supply.

The counties downwind of the NTS experienced fallout mostly as dry precipitate, and according to the agronomic data provided by the NCI, dairy cows in these areas consumed very little local pasture. This can create a substantial difference in the estimated exposure via milk versus estimated exposure via deposition.

$$ICM_{pij} = \int_0^\infty C_p(ijt) * P(ijt) * f_m dt \tag{3}$$

Equation (3) refers to the NCI's methodology for estimating daily I-131 concentrations in milk from deposition data. ICM_{pij} denotes the Integrated I-131 concentration in milk produced in pasture p in county i on day j and is measured in daily nCI per liter of milk. $C_p(ijt)$ denotes average daily concentration after deposition day. It is a function of deposition of I-131 and the fraction of this I-131 intercepted by plants. $P(ijt)$ denotes the average

---

[13] A small number of counties in both the deposition and milk measures consistent of sub county units. I created weighted averages of exposure at the county level from these subcounty units. In the analysis, these counties are excluded from the main sample. Other counties and Virginia Independent Cities are omitted from the sample due to data limitations.

pasture consumption rate by cows and was constructed from agronomic studies relating to pasturing behavior of dairy farmers during the 1950's. The value f_m denotes I-131 intake to milk transfer coefficient. This value was constructed from milk secretion studies where cows were fed radioactive iodine. These adjustments are made at the state level and should not be systematically correlated with any unobserved underlying economic or environmental conditions that would affect county mortality. The quantity of pasture a cow consumes on an average day and how long pastures are available to farmers during the year do not have any apparent relationship with crude death rates. These factors affect annual mortality rates only by altering the amount of I-131 entering the local food supply.

3 Empirical Results

3.1 Panel Regression Results

The empirical results suggest that fallout exposure due to NTS atomic testing led to persistent and sizable increases in mortality for large areas of the continental United States. The measured effect is generally larger for specifications using the milk exposure measure than the raw deposition measure. In the short run panel regressions, exposure to fallout through milk leads to immediate and sustained increases in the crude death rate. In the long run panel regressions, both deposition and the milk exposure regressions are associated with large increases in mortality following fallout exposure events. Finally, human exposure to fallout measured by I-131 in milk continues to have positive and statistically significant effects after the inclusion of state-by-year fixed effects, while the coefficients of the deposition measures attenuate towards zero.

Summary statistics for the sample used in the empirical regressions are provided in Table 1. Six different specifications are reported in each table of the empirical section. Specifications 1 through 3 report the effect using the milk exposure variable and specifications 4 through 6 report the effect using the deposition variable.[14] For both the milk and deposition measures, specifications with only fixed effects, including time trends, and the full specification are reported.

The discussion for the results refer to the specification with the most controls, which are specifications 3 and 6 in the tables. The results regarding short term mortality effects of radiation exposure appear in Table 2. Both milk exposure and deposition exposure measures are associated with increases in crude death rates over several years of lags. All of the milk exposure coefficients are statistically significant at the 5 percent level, but only the deposition coefficients for the first and second lags are statistically significant at the 10 percent level. Comparisons across specifications show that the inclusion of state-by-year fixed effects increases the magnitude of the estimated coefficients. The results suggest that 1,000 nCi of I-131 in the local milk supply leads to an additional 2.47 additional deaths per 10,000 residents in a given year, 2.89 deaths the subsequent year, 4.38 deaths two years later, 2.87 deaths three years later, and 2.71 four years later. The deposition estimates suggest that 1,000 nCi of deposition per m^2 increases the mortality rate by an additional 0.95 deaths per 10,000 two years following deposition and 0.88 deaths per 10,000 three years following deposition.

The long run mortality effects for both I-131 deposition and milk exposure channels appear in Table 3. Across most specifications there are positive and statistically significant increases in mortality attributable to NTS activities up to 25 years following the last atmospheric nuclear denotation at the NTS. Specifications including state-by-year fixed effects have negative coefficients on average exposure measures sixteen to twenty and twenty-one to twenty-five years following deposition. These results might arise from a harvesting effect if exposure to NTS fallout led to more people dying younger.

---

[14] Using both variables together introduce substantial multicollinearity but results in positive and statistically significant effects for the milk measures and statistically insignificant effects for deposition measures.

In specification 3, an average of 1,000 nCi in I-131 in milk one to five years prior contributes to an additional 12.93 deaths per 10,000 residents. An average of 1,000 a Ci in I-131 in milk six to ten years prior causes 7.04 additional deaths per 10,000. For average milk exposure eleven to fifteen years prior, and the coefficient reduces to 0.14 deaths per 10,000. The negative coefficients that appear after the inclusion of state-by-year fixed effects suggest that an average of 1,000 nCi in I-131 in milk sixteen to twenty and twenty-one to twenty-five years prior led to 7.89 and 5.78 fewer deaths per 10,000 individuals. Specification 6 finds no statistically significant and positive relationship between fallout deposition and mortality. The same coefficients for the exposure lags sixteen to twenty-five years following deposition suggest that 1,000 nCi of deposition led to 5.50 and 2.91 fewer deaths per 10,000. These coefficients are statistically significant at the 1 percent level.

3.2 Quantifying the Magnitude of the Effects and the Policy Implications of the Partial Nuclear Test Ban Treaty

The effects upon crude mortality are large relative to estimates by Simon and Bouville (2015) and comparable (or even larger) to the number of deaths attributable the atomic bombings of Hiroshima and Nagasaki. I perform a series of back-of-the envelope calculations to quantify the total mortality effect of NTS atomic testing. I use the long run coefficients of average exposure one to five, six to ten, and eleven to fifteen years prior to calculate this increase and then multiple them by the national crude death rate for the given year to estimate the total increase in the crude death rate per 10,000 individuals. I add together the three coefficients of interest to measure the total increase in the crude death rate for each specific county year observation between 1951 and 1973.[15] I multiply the estimated mortality effect by annual county populations and sum the totals across counties across years to estimate the total number of deaths attributable to atmospheric testing.[16]

---

[15] The final atmospheric test in my data was in 1958.

[16] Specification 6 is excluded from these calculations because it reports a null effect upon mortality.

Table 4 presents these calculated cumulative mortality effects. Depending on the regression specified, I-131 in milk contributed between 395,000 and 695,000 excess deaths from 1951 to 1973. The average increase in mortality across counties is between 0.65 and 1.21 additional deaths per 10,000 people for this same period. The estimates from deposition suggest that fallout contributed between 338,000 and 692,000 excess deaths over the same period. These effects are approximately 7 to 14 times larger than estimates provided by the NCI. When these effects are mapped out many of these estimated deaths occurred in regions far from the NTS. Figure 3 reports the average annual effects of radiation exposure through milk on mortality for years 1951 to 1973. Figure 4 reports the total increase in state deaths for the same period. The model suggests much of the death effect appears in the Midwest and Eastern U.S. where larger populations would have been exposed. The per capita mortality effects tend to be greatest out west in the Plains and in states north and east of the NTS.[17]

3.3 Robustness Checks

I perform a falsification test to test whether unobserved underlying factors were driving the crude death results. I select a sample of counties from 1937 to 1950 and reassigned the radiation exposure measures to the years of 1938, 1939, 1940, 1942, 1944, and 1945. The results are available in Table 5. I find no evidence that either the fallout deposition or fallout in milk measures had a systemic relationship with the log crude death rate between 1911 and 1950.[18]

---

[17] Running the regressions and including the excluded counties surround the NTS does not substantially change the patterns described in these maps.

[18] Additional robustness checks included taking the log of the exposure variable, adjusting the number of lags, including the excluded counties, and interacting the structural parameters used in calculating the milk measures with deposition. The mortality effect remains robust to specification choice. The inclusion of the excluded counties does not change the mortality effect for the dairy measures but introduces additional imprecision with the deposition estimates. This imprecision is resolved either through interacting the exposure variable with and indicator variable for these counties or by logging the treatment variable.

4 Policy Implications of Nuclear Testing

America's nuclear weapons program was (and still is) a costly national defense policy. From 1940 to 1996 the estimated cost of America's nuclear weapons program was approximately \$8.93 Trillion in 2016\$ (Schwartz, 2011). These monetary costs, however, do not fully capture the full social cost of America's nuclear weapons program. Since the 1990's the Federal Government has paid some compensation to victims of America's domestic nuclear weapons program. This compensation has focused on workers involved in the nuclear weapons program and those who lived downwind of the NTS during the 1950's. The U.S. Department of Justice pays out compensation to domestic victims of the nuclear weapons program through the Radiation Exposure Compensation Act. As of 2015 the U.S. Department of Justice has paid out over \$2 billion in compensation to victims (US Department of Justice, 2016).

Policy makers often assign accounting values to human lives when evaluating policy decisions. Viscusi (1993) and Viscusi and Aldy (2003) survey these valuations placed on human life. From 1988 to 2000, valuations of human life by U.S. Federal Government agencies ranged between \$1.4 million and \$8.8 million in 2016\$. These values and my estimates from the preferred specification place the value of lost life between \$473 billion and \$6,116 billion in 2016\$. Costa and Kahn (2004) use a hedonic wage regressions on industrial sector mortality risks to back out plausible market values for human life for each decade from 1940 to 1980. Using their values, I estimate the value of lost life from ground deposition between \$1.24 and \$2.56 trillion in 2016\$. The estimates from milk exposure places the value of lost life between \$1.17 and \$2.63 trillion. The social cost of excess deaths attributable to atmospheric testing at the NTS ranges from approximately 5.3 percent to 68.4 percent of the total cost of America's nuclear weapons program. These values, however likely understate the magnitude of the social costs of this polluting and environmentally destructive activities. Exposure to radioactive fallout likely made millions of people less healthy, negatively affected human capital, and increased the cost of providing health services to these populations. These costs are not fully captured by measuring the effect of nuclear testing upon mortality rates.

The cessation of atmospheric nuclear testing drastically reduced the release of harmful radioactive material into the air and likely saved many American lives. Two policies restricted atmospheric testing at the NTS. The first was a testing moratorium from 1958 to 1961, which moved almost all nuclear tests underground. The signing of the Partial Nuclear Test Ban Treaty ultimately ended all atmospheric nuclear tests by the U.S. in 1963. The cumulative kilo-tonnage of the atmospheric tests analyzed in this paper's data is 992.4kt. During the moratorium period the cumulative tonnage of underground testing at the NTS from 1958 to 1963 was 621.9kt. From 1963 to 1992, the total tonnage of nuclear explosions at the NTS was 34,327.9kt, approximately thirty-four times larger than the NTS atmospheric tests (US Department of Energy, 2000).[19]

Assuming that the domestic mortality effect of atmospheric testing is proportional to the tonnage of the weapons tests, one might estimate approximately how many American lives were saved by the moratorium period and the Partial Nuclear Test Ban Treaty. Multiplying the smallest and largest cumulative mortality effects by the ratio of the moratorium tonnage to atmospheric tonnage suggests that the moratorium possibly saved between 212,000 and 435,000 lives. Employing the same back of the envelope calculation, the Partial Nuclear Test Ban Treaty might have saved between 11.7 and 24.0 million American lives. These calculations have some caveats. First, it is likely that the transition to underground testing increased the size of the weapons tested. This likely would overestimate the potential effect of shifting underground testing above ground. Second, even without the moratorium and

---

[19] For the NTS, almost all tests were underground from 1958 to 1963. Some underground tests did not report bomb yields but instead ranges of yields. In these cases bomb yield was taken as the average value. In cases where the bomb yield was greater than a certain value, the lowest value was assigned.

treaty, there was mounting scientific and medical evidence that NTS activity were harmful to public health. It is likely that atmospheric testing at the NTS would have become politically untenable as more of the negative health effects associated with atmospheric testing became more pronounced. Finally, continuation of atmospheric testing likely would have increased repeated public exposure to radioactive fallout. This increase in average frequency of exposure might alter the point estimates identified in the panel regressions. Therefore, using the realized estimates might underestimate the potential effect of continued atmospheric testing upon mortality patterns.

The location of the NTS in Nye County, Nevada might have contributed towards the level of human exposure to radioactive pollution. In 1950, military and political leaders narrowed down list of potential atomic bombing ranges to a few locations (Schwartz, 2011). Other locations given serious consideration include the Trinity Test Site located in White Sands, New Mexico and Cape Hatteras, North Carolina. I use AP2 model from Muller et al. (2011) to construct a counter-factual scenario of potential pollution exposure from these alternative nuclear testing ranges. Nicholas Muller provided me a county to county matrix which measures the effect of pollution emissions from one source county on PM2.5 concentrations in all other counties. If radioactive dust created by atmospheric atomic tests follows similar dispersal patterns as other pollutants, then AP2 can provide a counter-factual scenario and rank counties by how polluting they could have been.

For all counties other than the source county, I weight the PM2.5 coefficients by county population in 1950. I then sum the cumulative effect of a single unit of emissions for each of the 3,100 source counties. This procedure allows me to rank the relative downwind effect of locating the NTS in an alternative county. Counties are ranked from least polluting to most polluting.[20] If policy makers sought to minimize human exposure to fallout, then

---

[20] I rank the relative dirtiness of the three mentioned locations and the top and bottom five alternative locations provided by the model in the Appendix.

the location of the NTS is quite fortunate. According to AP2, the NTS ranks 39th out of 3,100 counties. The White Sands and Cape Hatteras locations rank as the 953th and 495th least potentially polluting locations. Relatively speaking, White Sands would have been 3.45 times more polluting than the NTS and Cape Hatteras would have been 2.25 times more polluting.[21] These results show that atmospheric testing in the continental U.S. could have plausibly been much worse for American populations and public health if policy makers had chosen an alternative location.

5 Conclusion

This paper explores the temporal and geographic extent of the harm caused by atmospheric nuclear tests conducted in Nevada between 1951 and 1958. Using a new national dataset of radiation deposition and quantities of I-131 in the dairy supply, this paper finds that radiation exposure increased crude deaths in areas hundreds to thousands of miles from the test site. The geographic scope of the mortality consequences of NTS activities is broader than what previous research has shown. The largest health effects appear in areas far beyond the scope of previous scientific and medical studies. The scientific and medical literature has studied the effects of atmospheric testing on populations residing in Downwind counties in Arizona, Nevada, and Utah. Counter-intuitively, the areas where fallout had the largest impact on the crude death rate was not in the region surrounding the test site, but rather in areas with moderate levels of radioactive fallout deposition in the interior of the country. Due to pasturing practices, large quantities of fallout wound up in local dairy supplies in these regions but not in the Downwind region. It is quite plausible that extrapolating out the health effects from small samples of persons who lived around the NTS substantially underestimates the health costs associated with atmospheric testing.

---

[21] Intuitively the most polluting locations in the model would be the region surrounding New York City. These predictions are confirmed by the AP2 model. Interestingly, the Pacific Northwest, the Florida Keys, and Upstate Maine are locations that AP2 suggests would have been cleaner locations for testing than Nye, County.

The empirical results of this paper suggest that nuclear testing contributed to hundreds of thousands of premature deaths in the United States between 1951 and 1972. The social costs of these deaths range between \$473 billion to over \$6.1 trillion dollars in 2016\$. These losses dwarf the \$2 billion in payments the Federal Government has made to domestic victims of nuclear testing through the Radiation Exposure Compensation Act and are substantial relative to the financial cost of the United States' nuclear weapons program. It is likely that the values of both the testing moratorium enacted in 1958 and the Partial Nuclear Test Ban Treaty are understated. These political compromises likely saved hundreds of thousands of additional lives at a minimum.

The evidence presented in this paper reveals that the health cost of domestic nuclear testing is both larger and more expansive than previously thought. The mortality estimates may understate the magnitude of the true number of deaths attributable to nuclear testing and the magnitude of the health costs of this polluting defense policy. It is plausible that these estimates are lower bounds of the true health effects. Migration and measurement error in treatment introduces attenuation bias, and the health effects of radiation exposure may only appear later in life for many individuals. Millions of people who grew up during the testing period are now retiring from the labor force and are drawing upon Medicare and other government provided services. Nuclear testing may have made an entire generation of people less healthy and thus increased the cost of providing health care well into the present. This paper reveals that there are more casualties of the Cold War than previously thought, but the extent to which society still bears the costs of the Cold War remains an open question.

References

Almond, D., Chen, Y., Greenstone, M., and Li, H. (2009a). Winter Heating or Clean Air? Unintended Impacts of China's Huai River Policy. *American Economic Review*, 99(2):184–90.

Almond, D. and Currie, J. (2011). Killing me softly: The fetal origins hypothesis. *The Journal of Economic Perspectives*, 25(3):153–172.

Almond, D., Edlund, L., and Palme, M. a. (2009b). Chernobyl's subclinical legacy: prenatal exposure to radioactive fallout and school outcomes in sweden. *Quarterly Journal of Economics*, 124(4):1729–1772.

Bailey, M., Clay, K., Fishback, P., Haines, M., Kantor, S., Severnini, E., and Wentz, A. (2016). U.S. County-Level Natality and Mortality Data. Dataset ICPSR36603-v1, Inter-university Consortium for Political and Social Research, Ann Arbor, MI.

Ball, H. (1986). *Justice downwind: America's atomic testing program in the 1950s.* Oxford Press, New York, NY.

Barreca, A., Clay, K., and Tarr, J. (2014). Coal, Smoke, and Death: Bituminous Coal and American Home Heating. Working Paper 19881, National Bureau of Economic Research. DOI: 10.3386/w19881.

Beierwaltes, W. H., Crane, H. R., Wegst, A., Spafford, N. R., and Carr, E. A. (1960). Radioactive iodine concentration in the fetal human thyroid gland from fall-out. *JAMA*, 173(17):1895–1902.

Black, S. E., Bütikofer, A., Devereux, P. J., and Salvanes, K. G. (2013). This is only a test? long-run impacts of prenatal exposure to radioactive fallout. Working Paper w18987, National Bureau of Economic Research.

Center for Disease Control (2006). Report on the Health Consequences to the American Population from Nuclear Weapons Tests Conducted by the United States and Other Nations. Technical report.

Clay, K., Lewis, J., and Severnini, E. (2016). Canary in a Coal Mine: Infant Mortality, Property Values, and Tradeoffs Associated with Mid-20th Century Air Pollution. Working Paper 22155, National Bureau of Economic Research.

Clay, K., Troesken, W., and Haines, M. (2014). Lead and mortality. *Review of Economics and Statistics*, 96(3):458–470.

Costa, D. L. and Kahn, M. E. (2004). Changes in the Value of Life, 1940–1980. *Journal of risk and Uncertainty*, 29(2):159–180.

Currie, J. (2013). Pollution and Infant Health. *Child development perspectives*, 7(4):237–242.

Currie, J., Davis, L., Greenstone, M., and Walker, R. (2015). Environmental health risks and housing values: evidence from 1,600 toxic plant openings and closings. *The American economic review*, 105(2):678–709.

Danzer, A. M. and Danzer, N. (2016). The long-run consequences of Chernobyl: Evidence on subjective well-being, mental health and welfare. *Journal of Public Economics*, 135:47–60.

Dreicer, M., Bouville, A., and Wachholz, B. W. (1990). Pasture practices, milk distribution, and consumption in the continental US in the 1950s. *Health physics*, 59(5):627–636.

Flemming, A. S. (1959). Public exposure to radiation. *Public health reports*, 74(5):441.

Flemming, A. S. (1960). Strontium 90 content of wheat. *Public health reports*, 75(7):674.

Fradkin, P. L. (2004). *Fallout: An American Nuclear Tragedy.* Big Earth Publishing.

Garner, R. J. (1963). Environmental contamination and grazing animals. *Health physics*, 9(6):597–605.

Gilbert, E. S., Huang, L., Bouville, A., Berg, C. D., and Ron, E. (2010). Thyroid cancer rates and 131i doses from Nevada atmospheric nuclear bomb tests: an update. *Radiation research*, 173(5):659–664.

Hanlon, W. W. (2015). Pollution and Mortality in the 19th Century. Working Paper 21647, National Bureau of Economic Research.

Isen, A., Rossin-Slater, M., and Walker, W. R. (2017). Every breath you take—Every dollar you'll make: The long-term consequences of the Clean Air Act of 1970. *Journal of Political Economy*, 125(3):848–902.

Kerber, R. A., Till, J. E., Simon, S. L., Lyon, J. L., Thomas, D. C., Preston-Martin, S., Rallison, M. L., Lloyd, R. D., and Stevens, W. (1993). A cohort study of thyroid disease in relation to fallout from nuclear weapons testing. *Jama*, 270(17):2076–2082.

Kulp, J. L., Slakter, R., and others (1958). Current strontium-90 level in diet in United states. *American Association for the Advancement of Science. Science*, 128:85–86.

LeBaron, W. D. (1998). *America's nuclear legacy.* Nova Publishers.

Lee, S. (1999). Changes in the pattern of growth in stature related to prenatal exposure to ionizing radiation. *International journal of radiation biology*, 75(11):1449–1458.

Lehmann, H. and Wadsworth, J. (2011). The impact of Chernobyl on health and labour market performance. *Journal of health economics*, 30(5):843–857.

Muller, N. Z., Mendelsohn, R., and Nordhaus, W. (2011). Environmental Accounting for Pollution in the United States Economy. *American Economic Review*, 101(5):1649–1675.

National Cancer Institute (1997). Estimated Exposures and Thyroid Doses Received by the American People from Iodine-131 in Fallout Following Nevada Atmospheric Nuclear Bomb Tests. Technical Report Technical Report.

Olson, T. A. (1962). Strontium-90 in the 1959 United States Wheat Crop. *Science*, 135(3508):1064–1064.

Otake, M. (1996). Threshold for radiation-related severe mental retardation in prenatally exposed A-bomb survivors: a re-analysis. *International journal of radiation biology*, 70(6):755–763.

Otake, M., Fujikoshi, Y., Schull, W. J., and Izumi, S. (1993). A longitudinal study of growth and development of stature among prenatally exposed atomic bomb survivors. *Radiation research*, 134(1):94–101.

Schull, W. J. (1997). Brain damage among individuals exposed prenatally to ionizing radiation: a 1993 review. *Stem Cells*, 15(S1):129–133.

Schwartz, S. I. (2011). *Atomic audit: the costs and consequences of US nuclear weapons since 1940*. Brookings Institution Press.

Shibata, Y., Yamashita, S., Masyakin, V. B., Panasyuk, G. D., and Nagataki, S. (2001). 15 years after Chernobyl: new evidence of thyroid cancer. *The Lancet*, 358(9297):1965–1966.

Simon, S. L. and Bouville, A. (2015). Health effects of nuclear weapons testing. *The Lancet*, 386(9992):407–409.

Stevens, W., Thomas, D. C., Lyon, J. L., Till, J. E., Kerber, R. A., Simon, S. L., Lloyd, R. D., Elghany, N. A., and Preston-Martin, S. (1990). Leukemia in Utah and radioactive fallout from the Nevada test site: A case-control study. *Jama*, 264(5):585–591.

Troesken, W. (2008). Lead water pipes and infant mortality at the turn of the twentieth century. *Journal of Human Resources*, 43(3):553–575.

US Department of Energy (2000). United States Nuclear Tests July 1945 through September 1992. Technical Report Report DOE/NV-209-REV 15, US DOE. Nevada Operations Office, Las Vegas.

US Department of Justice (2016). RADIATION EXPOSURE COMPENSATION ACT.

Van Middlesworth, L. (1956). Radioactivity in thyroid glands following nuclear weapons tests. *Science*, 123(3205):982–983.

Viscusi, W. K. (1993). The value of risks to life and health. *Journal of economic literature*, 31(4):1912–1946.

Viscusi, W. K. and Aldy, J. E. (2003). The value of a statistical life: a critical review of market estimates throughout the world. *Journal of risk and uncertainty*, 27(1):5–76.

Williams, D. (2002). Cancer after nuclear fallout: lessons from the Chernobyl accident. *Nature Reviews Cancer*, 2(7):543–549.

Wolff, A. H. (1957). Radioactivity in animal thyroid glands. *Public health reports*, 72(12):1121.

Wolff, A. H. (1959). Milk contamination in the Windscale incident. *Public health reports*, 74(1):42.

Table 1: Summary Statistics

	mean	sd	count	min	max
Crude Death Rate (CDR) per 10,000	100.977	25.075	124,260	8.597	564.871
I-131 Deposition, 1,000's nCi	0.047	0.229	124,260	0	7.837
Avg Deposition 1 to 5 years prior, 1,000's nCi	0.052	0.141	124,260	0	6.608
I-131 in Milk, 1,000's nCi	0.030	0.136	124,260	0	4.600
Avg Milk 1 to 5 years prior, 1,000's nCi	0.032	0.079	124,260	0	1.857

Table 2: Short Run Mortality Effects, Crude Death Rate, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exposure, t	-0.113	0.997**	2.469**	0.181	-0.352	0.635
	(0.551)	(0.505)	(0.981)	(0.333)	(0.296)	(0.457)
Exposure, t-1	1.475***	2.115***	4.286***	1.029***	0.415	0.949*
	(0.524)	(0.461)	(0.764)	(0.297)	(0.275)	(0.566)
Exposure, t-2	2.006***	2.509***	4.379***	1.238***	0.689***	0.879**
	(0.570)	(0.493)	(0.937)	(0.277)	(0.246)	(0.406)
Exposure, t-3	1.554***	1.378***	2.287***	0.884***	0.320	0.556
	(0.514)	(0.461)	(0.852)	(0.282)	(0.279)	(0.462)
Exposure, t-4	2.866***	2.664***	2.708***	1.370***	0.806***	0.531
	(0.539)	(0.497)	(0.833)	(0.321)	(0.283)	(0.366)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.647	0.686	0.693	0.647	0.686	0.693

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All Standard Errors are Clustered by County. Exposure denotes the yearly cumulative I-131 measures at the county level.

Table 3: Long Run Mortality Effects, Crude Death Rate, 1940-1988

	(1)	(2)	(3)	(4)	(5)	(6)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exposure, t-1 to t-5	13.59***	11.29***	12.93***	7.734***	3.881***	1.878
	(1.684)	(1.584)	(2.774)	(1.264)	(1.204)	(2.083)
Exposure, t-6 to t-10	13.11***	8.676***	7.041**	6.797***	3.501***	-0.362
	(1.599)	(1.565)	(2.962)	(1.263)	(1.181)	(1.794)
Exposure, t-11 to t-15	10.39***	4.854***	0.143	5.314***	2.346**	-1.507
	(1.662)	(1.588)	(2.888)	(1.167)	(1.018)	(1.425)
Exposure, t-16 to t-20	7.239***	1.411	-7.894**	2.667**	0.0859	-5.502***
	(1.786)	(1.680)	(3.520)	(1.140)	(0.979)	(1.353)
Exposure, t-21 to t-25	7.834***	-2.317	-5.779**	2.513***	0.0434	-2.909***
	(1.915)	(1.414)	(2.801)	(0.847)	(0.587)	(1.110)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.648	0.686	0.693	0.648	0.686	0.693

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All Standard Errors are Clustered by County. Exposure denotes the pooled five year averages of cumulative I-131 measures at the county level.

Table 4: Changes in County Mortality Patterns Attributable to NTS Fallout, 1951 to 1973

I-131 In Local Milk

	Mean	SD	Max	Total Deaths
Specification 1	1.208	1.899	26.259	695,436.300
Specification 2	0.806	1.320	20.975	458,506.700
Specification 3	0.649	1.280	24.012	359,360.700

I-131 Ground Deposition

	Mean	SD	Max	Total Deaths
Specification 4	1.056	1.779	51.102	692,407.400
Specification 5	0.517	0.883	25.644	338,472.700
Specification 6	-	-	-	-

Source: Author's calculations

Table 5: Placebo Test: Log Crude Death Rate, 1937-1950

	(1)	(2)	(3)	(4)	(5)	(6)
	Milk Placebo , 1,000's nCi			Deposition Placebo, 1,000's nCi		
Exposure, t	-1.215*	-0.476	-1.563	-0.339	-0.461	-0.232
	(0.688)	(0.707)	(1.751)	(0.269)	(0.281)	(0.369)
Exposure, t-1	-0.511	-1.216**	-3.388	-0.297	-0.480	-0.460
	(0.589)	(0.594)	(2.425)	(0.298)	(0.312)	(0.647)
Exposure, t-2	0.548	-1.219**	0.189	-0.114	-0.333	-0.0243
	(0.570)	(0.584)	(0.903)	(0.246)	(0.266)	(0.307)
Exposure, t-3	2.999***	0.651	0.603	0.525**	0.258	-0.111
	(0.624)	(0.621)	(0.970)	(0.234)	(0.230)	(0.351)
Exposure, t-4	2.824***	-0.589	1.055	0.464*	0.0748	0.0660
	(0.589)	(0.600)	(0.867)	(0.255)	(0.247)	(0.334)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	42,096	42,096	42,096	42,096	42,096	42,096
Adj r^2	0.607	0.615	0.618	0.606	0.615	0.618

All Standard Errors are Clustered by County. Placebo Exposure denotes the yearly cumulative I-131 measures at the county level. These placebo measures consist of I-131 measures being shifted forward thirteen years. i.e. Exposure in 1951 recoded as 1938, 1952 as 1939, 1953 as 1940, etc. Three tests for 1945 were conducted in New Mexico but their yields were relatively small. The corresponding Hardtack tests of 1958 were also small in scale and most radiation release remained near the Nevada test site in 1958.

Table 6: AP2 Ranking of 3,100 Alternative Nuclear Test Site Locations

Location	**Pollution Intensity**	**Rank**
Locations Under Consideration by Policy Makers		
Nevada Test Site (Nye County), NV	1	39
White Sands (Dana Ana County), NM	3.327	953
Cape Hatteras (Dare County), NC	2.167	495
Top Five Least Polluting Counties		
Modoc County, CA	0.251	1
Lake County, OR	0.303	2
Monroe County FL	0.342	3
Klamath County, OR	0.394	4
Del Norte County, CA	0.394	5
Top Five Most Polluting Counties		
Nassau County, NY	186.829	3,096
Essex County, NJ	196.218	3,097
Hudson County, NJ	262.022	3,098
Bergen County, NJ	362.736	3,099
Queens County, NY	440.651	3,100

Parameters for AP2 provided by Nicholas Muller. Rank denotes order of least polluting counties 1 to 3,100. Pollution intensity denotes population weighted PM2.5 exposure for all recipient counties relative to the NTS. Emission location is excluded from the calculation.

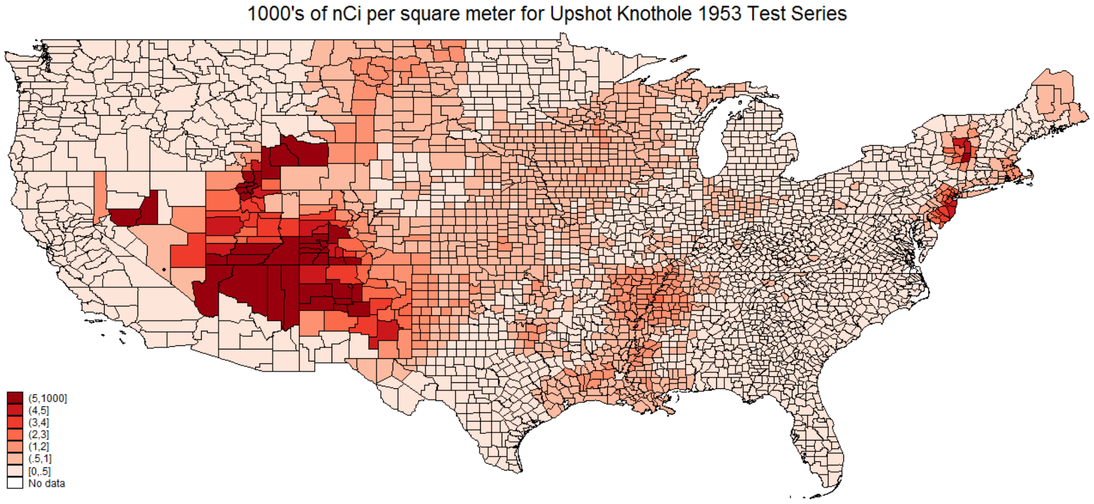


Figure 1: Cumulative I-131 Deposition from Upshot Knothole Series. Source: Created from NCI data.

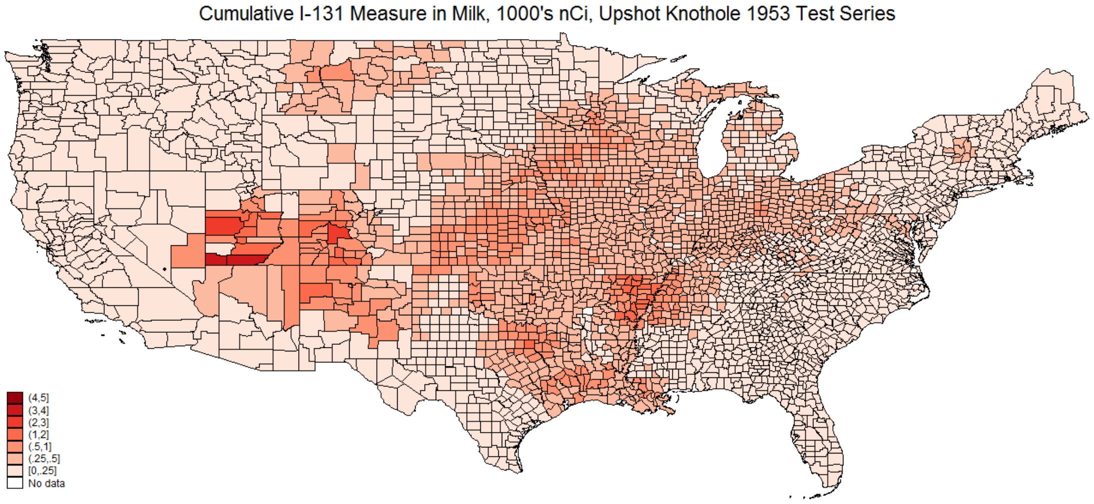


Figure 2: Cumulative I-131 Milk Measures from Upshot Knothole Series. Source: Created from NCI data.

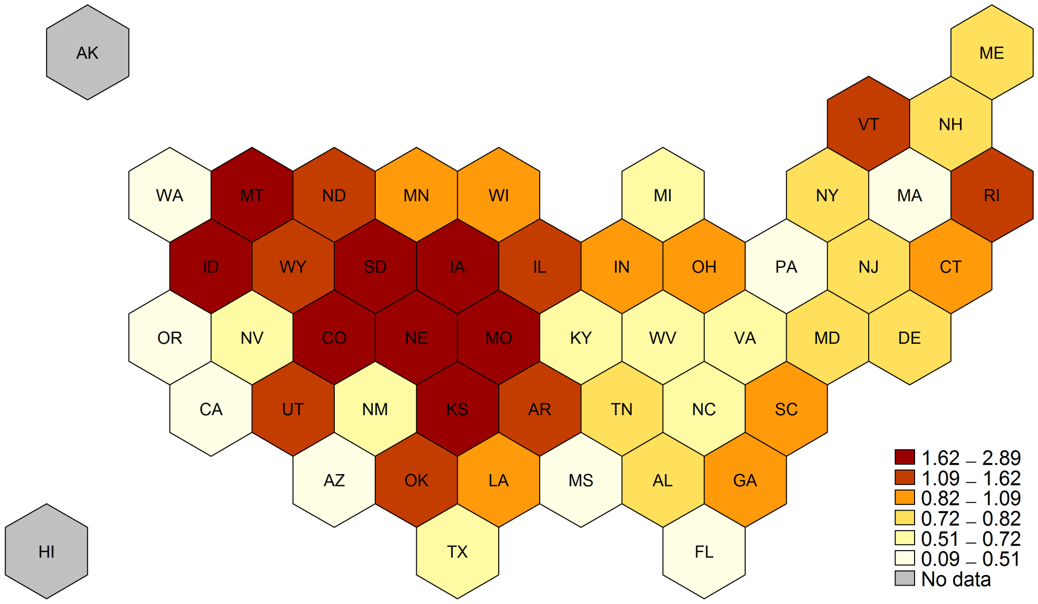


Figure 3: Average Increase in Crude Deaths Per 10,000 attributable to I-131 in Milk, 1951 to 1973. Source: Author's calculations

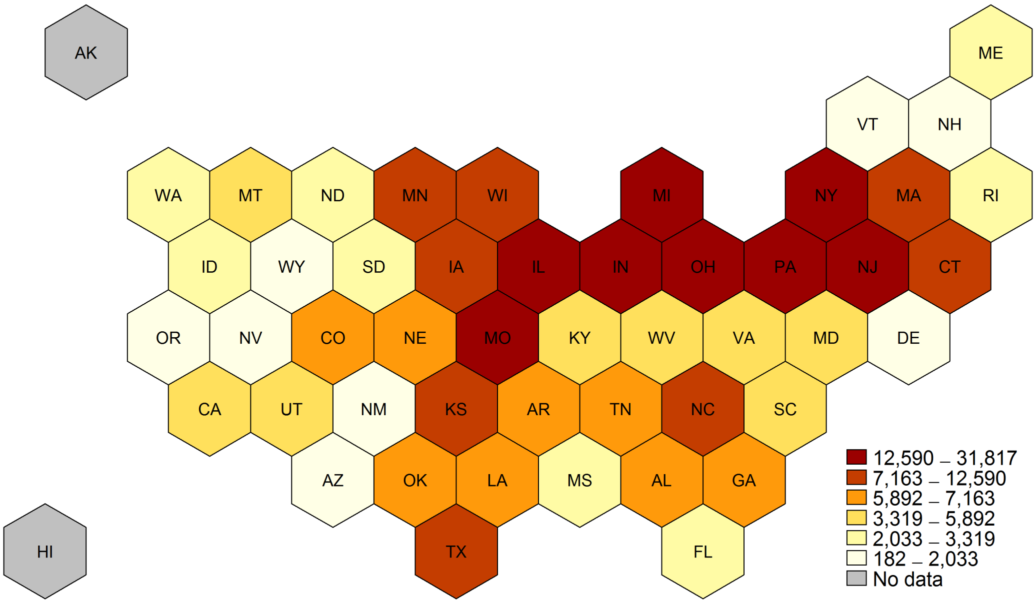


Figure 4: Total Increase in Crude Deaths to I-131 in Milk, 1951 to 1973. Source: Author's calculations

A Alternative Model Specification and Calculations

Table A1: Short Run Mortality Effects, Log Crude Death Rate Conditioned on Log Population, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exposure, t	0.0410***	0.0126**	0.0276***	0.00910***	-0.00638**	0.00393
	(0.00609)	(0.00499)	(0.00985)	(0.00340)	(0.00283)	(0.00447)
Exposure, t-1	0.0521***	0.0190***	0.0391***	0.0147***	0.00178	0.00716
	(0.00546)	(0.00489)	(0.00793)	(0.00387)	(0.00255)	(0.00531)
Exposure, t-2	0.0590***	0.0259***	0.0437***	0.0162***	0.00647**	0.00770*
	(0.00528)	(0.00446)	(0.00846)	(0.00359)	(0.00254)	(0.00407)
Exposure, t-3	0.0416***	0.0133***	0.0230**	0.0128***	0.00270	0.00564
	(0.00550)	(0.00481)	(0.00930)	(0.00371)	(0.00272)	(0.00499)
Exposure, t-4	0.0516***	0.0280***	0.0283***	0.0169***	0.00675**	0.00301
	(0.00534)	(0.00512)	(0.00836)	(0.00399)	(0.00293)	(0.00380)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.725	0.752	0.755	0.724	0.752	0.755

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Panel includes controls for log population. Exposure denotes the yearly cumulative I-131 measures at the county level.

Table A2: Short Run Mortality Effects, Log Crude Death Rate, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exposure, t	0.00776	0.0143**	0.0284**	0.00396	-0.00653**	0.00626
	(0.00597)	(0.00555)	(0.0111)	(0.00385)	(0.00323)	(0.00517)
Exposure, t-1	0.0216***	0.0236***	0.0441***	0.0127***	0.00283	0.00994*
	(0.00583)	(0.00515)	(0.00852)	(0.00339)	(0.00286)	(0.00598)
Exposure, t-2	0.0293***	0.0302***	0.0510***	0.0159***	0.00771***	0.0107**
	(0.00584)	(0.00498)	(0.0103)	(0.00319)	(0.00268)	(0.00480)
Exposure, t-3	0.0213***	0.0169***	0.0303***	0.0122***	0.00359	0.00792
	(0.00562)	(0.00501)	(0.00961)	(0.00343)	(0.00299)	(0.00559)
Exposure, t-4	0.0341***	0.0298***	0.0339***	0.0162***	0.00771**	0.00519
	(0.00583)	(0.00536)	(0.00918)	(0.00365)	(0.00314)	(0.00437)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.661	0.699	0.705	0.661	0.698	0.705

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Panel excludes controls for log population.
Exposure denotes the yearly cumulative I-131 measures at the county level.

Table A3: Long Run Mortality Effects, Log Crude Death Rate Conditioned on Log Population, 1940-1988

	(1)	(2)	(3)	(1)	(2)	(3)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exposure, t-1 to t-5	0.244***	0.113***	0.120***	0.0940***	0.0388***	0.0245
	(0.0168)	(0.0138)	(0.0261)	(0.0179)	(0.0113)	(0.0203)
Exposure, t-6 to t-10	0.147***	0.0783***	0.0477*	0.0760***	0.0385***	0.00872
	(0.0137)	(0.0127)	(0.0261)	(0.0146)	(0.0108)	(0.0169)
Exposure, t-11 to t-15	0.0958***	0.0507***	-0.00304	0.0565***	0.0311***	0.0128
	(0.0139)	(0.0133)	(0.0261)	(0.0123)	(0.00962)	(0.0148)
Exposure, t-16 to t-20	0.0324**	0.0155	-0.0813***	0.0258**	0.0128	-0.0265**
	(0.0146)	(0.0143)	(0.0301)	(0.0105)	(0.00951)	(0.0126)
Exposure, t-21 to t-25	-0.0411***	-0.0113	-0.0674***	0.00583	0.00806	-0.0148
	(0.0148)	(0.0127)	(0.0242)	(0.00705)	(0.00614)	(0.0102)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.726	0.752	0.755	0.725	0.752	0.755

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All Standard Errors are Clustered by County. Panel includes controls for log population. Exposure denotes the pooled five year averages of cumulative I-131 measures at the county level.

Table A4: Long Run Mortality Effects, Log Crude Death Rate, 1940-1988

	(1)	(2)	(3)	(4)	(5)	(6)
	Milk Exposure, 1,000's nCi			Deposition Exposure, 1,000's nCi		
Exposure, t-1 to t-5	0.159***	0.124***	0.158***	0.0972***	0.0453***	0.0304
	(0.0190)	(0.0171)	(0.0331)	(0.0165)	(0.0141)	(0.0253)
Exposure, t-6 to t-10	0.130***	0.0832***	0.0906***	0.0820***	0.0424***	0.00560
	(0.0165)	(0.0161)	(0.0327)	(0.0152)	(0.0131)	(0.0199)
Exposure, t-11 to t-15	0.0976***	0.0428***	0.0190	0.0669***	0.0342***	0.00256
	(0.0172)	(0.0165)	(0.0329)	(0.0144)	(0.0122)	(0.0186)
Exposure, t-16 to t-20	0.0571***	0.00274	-0.0781**	0.0393***	0.0143	-0.0423***
	(0.0173)	(0.0166)	(0.0342)	(0.0139)	(0.0121)	(0.0156)
Exposure, t-21 to t-25	0.0638***	-0.0244	-0.0656**	0.0229**	0.00429	-0.0300**
	(0.0197)	(0.0154)	(0.0312)	(0.0105)	(0.00760)	(0.0131)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
State Time Trends	No	Yes	No	No	Yes	No
State Year FE	No	No	Yes	No	No	Yes
N	124,260	124,260	124,260	124,260	124,260	124,260
Adj r^2	0.662	0.699	0.705	0.663	0.699	0.705

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All Standard Errors are Clustered by County. Panel excludes controls for log population. Exposure denotes the pooled five year averages of cumulative I-131 measures at the county level.

Table A5: Changes in County Mortality Patterns Attributable to NTS Fallout, 1951 to 1973

	I-131 Ground Deposition			
Table A3	Mean	SD	Max	Total Deaths
Specification 1	1.626	2.695	48.637	919,930.300
Specification 2	0.772	1.258	21.153	438,896.900
Specification 3	0.521	1.091	22.392	285,953.800

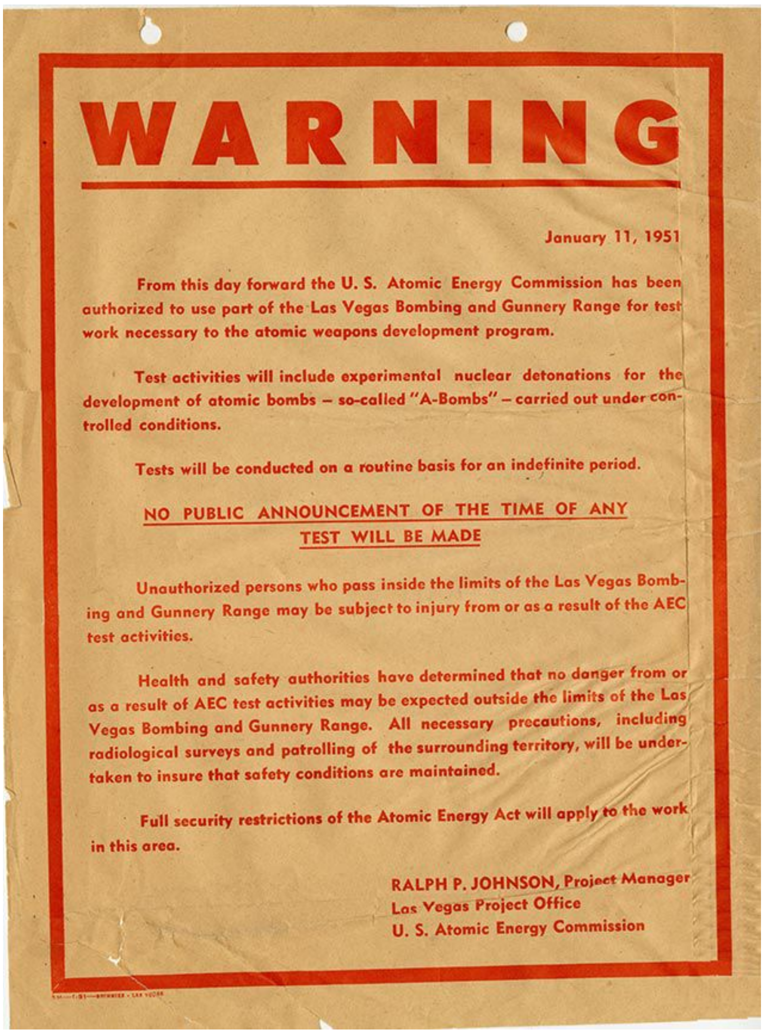
	I-131 Ground Deposition			
Table A3	Mean	SD	Max	Total Deaths
Specification 4	1.176	1.999	61.394	768,609.900
Specification 5	0.553	0.928	24.857	363,744.700
Specification 6	0.230	0.397	15.414	149,369.400

	I-131 in Local Milk			
Table A4	Mean	SD	Max	Total Deaths
Specification 1	1.265	2.009	30.404	724,033.300
Specification 2	0.797	1.337	23.163	450,844.700
Specification 3	0.865	1.603	30.219	482,489.200

	I-131 Ground Deposition			
Table A4	Mean	SD	Max	Total Deaths
Specification 4	1.283	2.158	63.592	840,690.700
Specification 5	0.623	1.046	28.852	409,208.300
Specification 6	0.191	0.425	19.209	119,680.600

Source: Author's calculations.

B Additional Figures



WARNING

January 11, 1951

From this day forward the U. S. Atomic Energy Commission has been authorized to use part of the Las Vegas Bombing and Gunnery Range for test work necessary to the atomic weapons development program.

Test activities will include experimental nuclear detonations for the development of atomic bombs – so-called "A-Bombs" – carried out under controlled conditions.

Tests will be conducted on a routine basis for an indefinite period.

NO PUBLIC ANNOUNCEMENT OF THE TIME OF ANY TEST WILL BE MADE

Unauthorized persons who pass inside the limits of the Las Vegas Bombing and Gunnery Range may be subject to injury from or as a result of the AEC test activities.

Health and safety authorities have determined that no danger from or as a result of AEC test activities may be expected outside the limits of the Las Vegas Bombing and Gunnery Range. All necessary precautions, including radiological surveys and patrolling of the surrounding territory, will be undertaken to insure that safety conditions are maintained.

Full security restrictions of the Atomic Energy Act will apply to the work in this area.

RALPH P. JOHNSON, Project Manager
Las Vegas Project Office
U. S. Atomic Energy Commission

Figure A1: 1951 NTS Waring Flyer: Source U.S. Department of Energy Nuclear Testing Archive

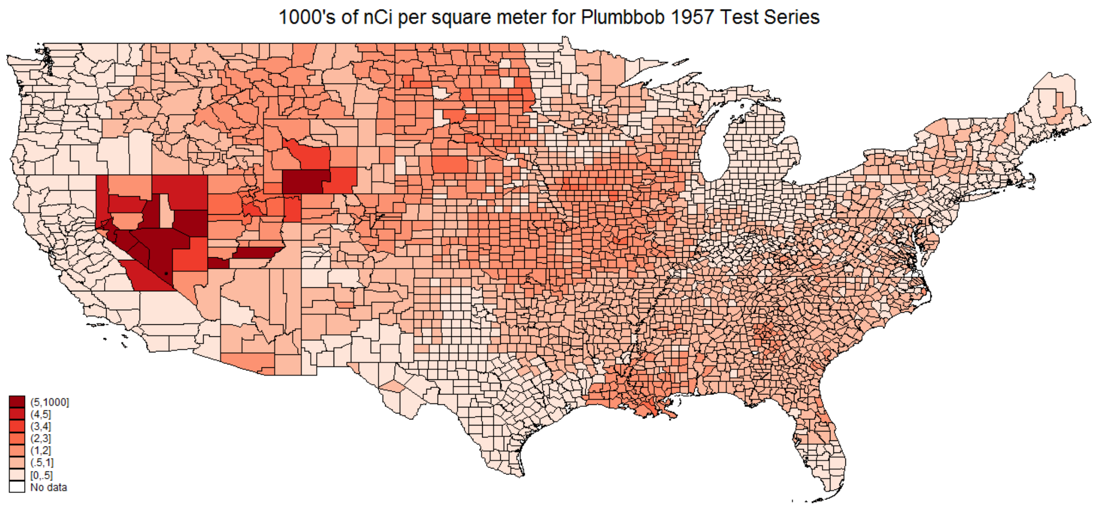


Figure A2: Cumulative I-131 Deposition from Plumbbob Series. Source: Created from NCI data.

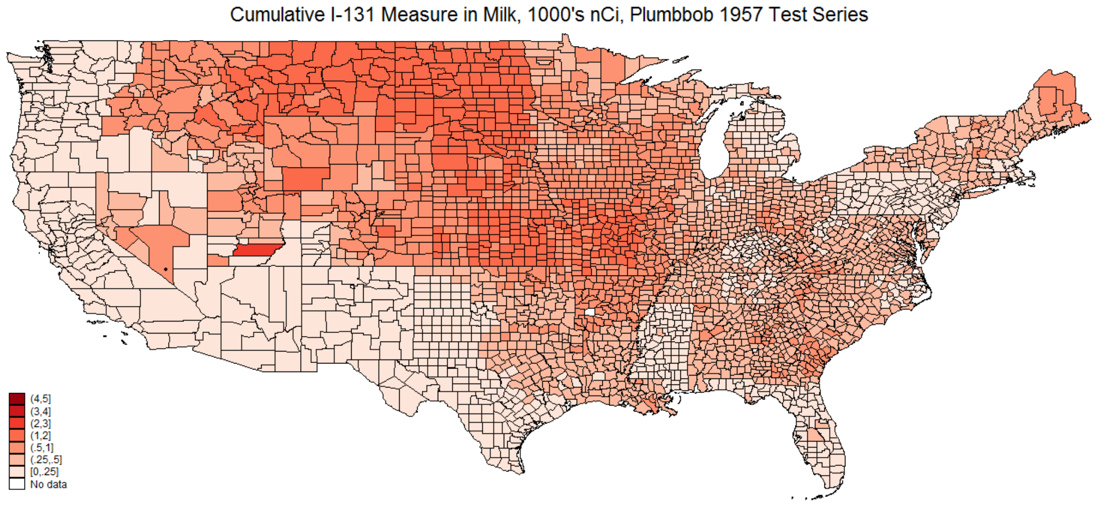


Figure A3: Cumulative I-131 Milk Measures from Plumbbob Series. Source: Created from NCI data.

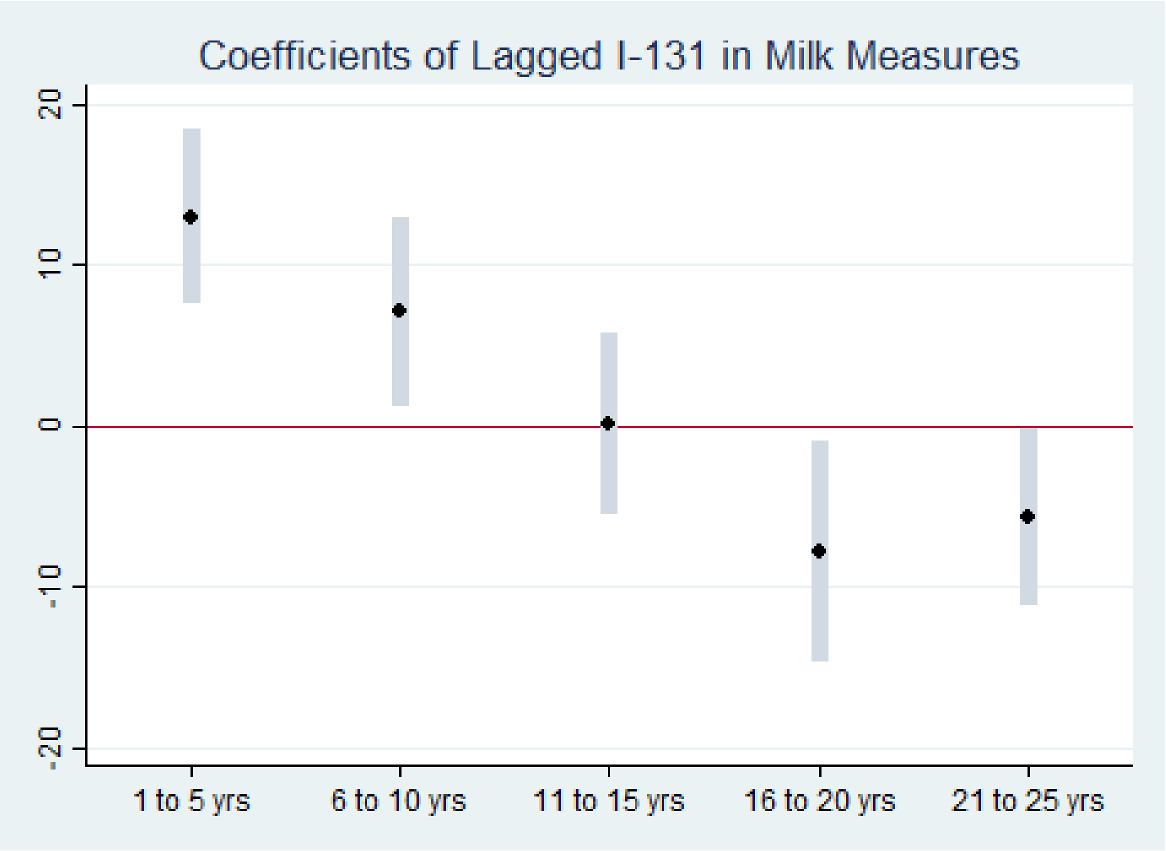


Figure A4: Coefficients on Lagged Milk Measures on Crude Deaths, 95% CI. Source: Author's calculations