# ASSOCIATION BETWEEN THYROID CANCER INCIDENCE AND THE DISTANCE FROM NUCLEAR POWER PLANTS IN THE U.S.

By

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A Thesis

Presented to the Department of Public Health and Preventive Medicine

and the Oregon Health and Science University School of Medicine

in partial fulfillment of the requirements for the degree of

Master of Public Health

June 2012

School of Medicine

Oregon Health & Science University

CERTIFICATE OF APPROVAL

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**Acknowledgements**

I am proud to know so many wonderful professors and faculty that have shared so much knowledge with me over past two years at OHSU.

I am grateful to my thesis committee, Drs. Dongseok Choi, Neil Gross, and Thomas Becker. Each has provided tremendous support, mentorship, and encouragement throughout this project. Their commitment to public health and education has inspired me and changed the course of my career.

Finally, my completion of the MPH program would not have been possible without the significant support of my husband, Taketo, and my daughter, Sara.

**Abstract**

Concerns have been widespread that living near nuclear power plants might increase the risk of cancer in surrounding communities. Nuclear power generation is still the most powerful alternative energy; however, we should remind ourselves of its health effects. Studies of the association between living close to nuclear power plants and the risk of cancer, including thyroid cancer, have shown mixed results. The thyroid gland is highly sensitive to the carcinogenic effects of radiation. Few previous studies have shown an association between living close to nuclear power plants and thyroid cancer incidence among people of all ages in the United States (U.S.). The northeastern area has the highest concentration of nuclear power plants in the U.S. Most of the incidence rates close to nuclear power plants in the area were over the U.S. rate, which is 11.0 per 100,000 person-years. Incidence rates of thyroid cancer were quantified and compared between <15 mile, 15 ~ <30 mile, and 30 ~ <45 mile radius from the nearest nuclear power plant. A multivariate mixed-effect model was fitted to characterize the association between the distance <15 mile, 15 ~ <30 mile, and 30 ~ <45 mile zone from the nearest nuclear power plant and incidence rates of thyroid cancer, adjusting for potential confounding variables. After adjusting for confounding variables, the incidence rates of thyroid cancer were not associated with the distance (mile zone) from the nearest nuclear power plant ( $\beta$ ~N(-0.003, 0.01) p = 0.872). Our study showed no association between the distance from a nuclear power plant and incidence rates of thyroid cancer in the U.S.

## Research Question

Is there an association between the distance from a nuclear power plant and the incidence rate of thyroid cancer among men and women of all ages in the U.S.? Does the association differ by demographics in the study areas, number of reactors per plant, and/or the length of operation?

## Specific Aims

Using the 2004-2008 State Cancer Profile data set, our specific aims were to:

1. Identify incidence rates of thyroid cancer for people who live in <15 mile, 15 ~ <30 mile, and 30 ~ <45 mile zone from the nearest nuclear power plant in the U.S.

2. Identify demographics, the number of reactors, the length of operation for each nuclear power plant in the study zones, and analyze their associations with the incidence rates of thyroid cancer in the study zones.

## Background

Fukushima Daiichi nuclear disaster in Japan, following the 2011 Tohoku earthquake and tsunami, was a great shock to people all over the world. The Fukushima disaster is the largest nuclear accident since the 1986 Chernobyl disaster. More than 20 years after the Chernobyl disaster, nuclear power generation attracted worldwide attention again. People are worried about the potential dangers and health effects of nuclear power plants. Although nuclear power energy is still the most viable alternative energy, we should understand clearly the health effects and risks of nuclear power plants.

## Nuclear power plants in the U.S

As of 2011, 104 commercial reactors were operating at 65 nuclear power plants in the United States, producing a total of 806 TWh of electricity, which is almost 20% of the total U.S. electric energy generation (Nuclear Energy Review). The United States is the world's largest supplier of commercial nuclear power.

## Nuclear power plants and the risk of cancer in the U.S.

Studies of the association between the risk of cancer and distance from nuclear power plants have shown mixed results. Clapp et al (1987) reported an excess incidence of leukemia in men in five towns near the Pilgrim nuclear power station in Massachusetts. Seymour et al (1991) reported that no general increase in cancer mortality was found in counties in the U.S. with or near nuclear electricity generating plants and no excess incidence of leukemia was found in children who lived near reprocessing and weapon plants. Mangano et al (2009) found that 11 of the 18 counties (population over 88,000) with the highest incidence rates of thyroid cancer are clustered within a 90-mile radius in New Jersey, southern New York and eastern Pennsylvania. This area has 16 nuclear power reactors at seven plants, the highest concentration of reactors in the U.S.

## Nuclear power plants and the risk of cancer in other countries

Elevated childhood cancer incidence rates close to nuclear facilities have been reported in Canada (Sharp, McKinney et al. 1999), France (Viel, Richardson et al. 1993), and the former Soviet Union (Zaridze, Li et al. 1994). A case-control study in Germany from 1980-2003 found an increased risk for childhood cancer under five years among people living within 5 km from nuclear power plants (odds ratio 1.47; lower one-sided 95% confidence limit 1.16) (Spix, Schmiedel et al. 2008). On the other hand, the nationwide cohort study found little evidence of an association between residence near nuclear power plants and the risk of any childhood cancer in Switzerland (Spycher, Feller et al. 2011).

## The risk of radiation exposure and nuclear power plants

Although the amount of airborne and liquid radioactive emissions from nuclear power plants should be variable over time, large increases often remain high for extended periods of time. Radioactive levels in bodies (internal radiation exposure) are also important, and the Radiation and Public Health Project (RPHP) measured Sr-90, whose half-life is 28.7 years, in baby teeth. A comprehensive analysis of five published medical journal articles found that the average amount of Sr-90 in baby teeth was 30-50% higher in counties closest to six U.S. nuclear plants (Mangano, Gould et al. 2003).

**Radiation and the risk of thyroid cancer**

Several studies have shown that the thyroid gland is highly sensitive to the carcinogenic effects of radiation. Ionizing radiation has been likely been associated with the increased risk of thyroid tumors.  Studies of atomic bomb survivors in Hiroshima and Nagasaki have demonstrated increased risk for thyroid nodules, which include cancer (Nagataki, Shibata et al., 1994). On March 28,1979, the nuclear exposure incident occurred at the Three Mile Island (TMI) nuclear power plant. Small quantities of xenon and iodine radioisotopes were released into the environment. One of three counties around the plant showed a significant increase in thyroid cancer incidence, and another county demonstrated a trend toward increasing thyroid cancer incidence approximately 10 and 15 years after the TMI accident respectively (Levin 2008). A decade after the Chernobyl nuclear power plant accident, an increase in thyroid cancer incidence was observed in those exposed to radiation as children or adolescents at the time of accident (Ron 2007).

The Hanford Thyroid Disease Study is a study of thyroid disease among people who were exposed to radioactive iodine (iodine-131) from the Hanford Nuclear Site in Washington State. Iodine-131 was released into the air from Hanford from 1944 through 1957. The Hanford Thyroid Disease Study (2002) showed that no association between Hanford's iodine-131 releases and thyroid disease, including thyroid cancer, was observed (Reynolds 2002).

**Thyroid Cancer Trends in the U.S.**

Thyroid cancer accounted for about 10% of all malignancies diagnosed in individuals 15 to 29 years of age and was the fourth most common cancer in this age group. Between 1975 and 2000, the incidence of thyroid cancer increased steadily at a statistically significant rate. Most of the increase occurred during the 1990s. Overall, the most significant increase in incidence was observed in those individuals 45 years of age and older, but these changes were statistically significant in all age groups (SEER AYA Monograph). Reasons for this increase in thyroid cancer incidence are not clear, but can be attributable to the improvement in diagnostic equipment. However, other possible explanations including environmental radiation exposure should be explored.

We have investigated the association between distance from the nuclear power plant and thyroid cancer incidence in the U.S. Although the long-term future of nuclear power in the U.S. remains uncertain, the results will serve as a guide to increase the safety of nuclear power plants worldwide and raise awareness to the health dangers associated with living near a nuclear power plant.

## Methods

### 1. Overview

This was a cross-sectional study using the State Cancer Profile data to determine the association between incidence rates of thyroid cancer and distance from the nearest nuclear power plant all over the U.S.

National U.S. thyroid cancer incidence data were available only by the county level, and not the individual or sub-county level. Because we wanted to study the association between living close to nuclear power plants and thyroid cancer incidence, we used Arc GIS and estimated the incidence rates at 15 mile intervals from the nearest nuclear power plants.

### 2.Original Data

**State Cancer Profiles Data**

The National Cancer Institute (NCI) staff work with the North American Association of Central Cancer Registries (NAACCR) to guide all state registries to achieve data content and compatibility acceptable for pooling data and improving national estimates. The Surveillance Epidemiology and End Result (SEER) team is developing computer applications to unify cancer registration systems and to analyze and disseminate population-based data. Use of surveillance data for research is being improved through Web-based access to the data and analytic tools, and linking with other national data sources. State Cancer Profile is one of these.

The State Cancer Profile website has state-based cancer incidence data for all states and the District of Columbia from 2004-2008. The database includes county-specific data for all states, excluding Minnesota and Kansas, Broomfield County in Colorado and Menominee County in Michigan. The source of some states' data is SEER, while for other it's State Cancer Registry and the Centers for Disease Control and Prevention's (CDC) National Program of Cancer Registries Cancer Surveillance System (NPCR-CSS). Incidence rates are published only for those counties with at least 15 thyroid cases diagnosed in 2004-2008, as rates in less-populated counties are based on small numbers of cases that are often not reliable. Incidence rates (cases per 100,000 population per year) were age-adjusted to the 2000 U.S. standard population (19 age groups: <1, 1-4, 5-9, … , 80-84, 85+).

## 3.Methods of Measurements

### Main Predictor Variable

The main predictor variable was the distance (mile zone) from the nuclear power plant, which was grouped into three zones: <15 mile, 15 ~ <30 mile, and 30 ~ <45 mile zones from the nearest nuclear power plants. Because there was overlap of some zones from the nearest nuclear power plants, the multiple zones were combined to avoid double counting using ArcGIS. The all-combined zones were called "Area" (Figure 1).

The information for all operating commercial nuclear power reactors that generated electricity at the end of 2008 is available on U.S. NRC (United States Nuclear Regulatory Commission) (http://www.nrc.gov/) and Department of Energy (http://energy.gov/) websites. There are 65 commercial nuclear electric plants, which have 107 reactors all over the U.S.

**Potential Confounding Variables**

We considered the following potential confounding variables (Table 1). Selected demographic characteristics in the study areas were from the 2000 U.S. Census report, because the incidence rates in the state cancer profile data set are age-adjusted to the 2000 U.S. standard population. The characteristics of each nuclear power plant were from U.S. NRC and Energy.gov/Department of Energy websites.

**Outcome Variables**

Incidence rates of thyroid cancer were analyzed for areas situated <15 mile, 15 ~ <30 mile, and 30 ~ <45 mile from the nearest nuclear power plant in the U.S. The analysis focused on incidence rates of thyroid cancer among men and women of all ages, who resided in the study zones at the time of diagnosis. The incidence rates of areas <15 mile, 15 ~ <30 mile, and 30 ~ <45 mile zone were computed by the following steps using ArcGIS, because cancer rates are not available at the subcounty nor the individual level. In State Cancer Profile, counts (average cases per year over 2004-2008) are suppressed if counts are fewer than 16 cases (average cases per year over 2004-2008 are fewer than 3cases). We assumed that average case was 1 if the population was over 15,000, and 0 if population was under 15,000.

*Steps for calculating incidence rates for thyroid cancer in a study zone X that overlaps with Counties A and B* (See also Figure 2 for illustration):

1. The distance from the nuclear power plant was calculated.
2. Dissolve: Aggregate the study zones
3. Intersect: Cut the study zone from county “A” and “B” to produce area “a” and “b”.
4. Calculate area “A”, “B”, “a” and “b”.
5. Calculate the proportions of subareas in a study zone intersecting with all surrounding counties: for example,

   a1 = area “a” / area “A”,

   b1 = area “b” / area “B”
6. Calculate average cases per year from 2004-2008 and population in 2004 for the study zone of each county: for example,

   average cases for area “a” , a2 = average cases for county “A” * a1

   population for area “a”, A2 = population for county “A” * a1
7. Calculate the average cases and population for the study zone area: for example,

average case for zone “X” = a2 + b2 (sum over average cases for area “a” with “b”)

population for zone “X” = A2 + B2 (sum over population for area “a” with “b”)

8. Calculate incidence rate of thyroid cancer with the study zone area: for example,

incidence rate with zone “X” = (a2 + b2) / (A2 + B2)

(average cases for zone “X” / population for zone “X” )

Examining rates on a smaller scale might be of interest; however, achieving statistical significance would be difficult because only small population reside near the plants in general. Incidence rates of thyroid cancer in 2004-2008 were examined for areas near all nuclear power plants in operation at the end of 2008. Because there was overlap of some zones from the nearest nuclear power plants, the multiple zones were combined to avoid double counting using ArcGIS.

## 4.Data Analysis

**Aim1**

Age-adjusted incidence rates of thyroid cancer in 2004-2008 by county and location of nuclear power plants in the U.S. were visualized in illustration to the association across the U.S. on the choropleth map.

Descriptive analyses were performed for crude incidence rates of thyroid cancer in the study areas (< 15 mile, 15 ~ < 30 mile, and 30 ~ < 45 mile zone) in

2004-2008. Line graphs showed the trend of incidence rates of thyroid cancer by distance (mile zone) from the nearest nuclear power plant for each region.

**Aim2**

As a baseline mixed effect model, incidence rates of thyroid cancer for various areas were analyzed by distance (< 15 mile, 15 ~ < 30 mile, and 30 ~ < 45 mile zone) from the nearest nuclear power plant. Demographics and social and economic variables in the study areas are tested one at a time by being added to the baseline model. Based on the result, variables were selected for final model using backward selection ($p > 0.05$).

A multivariate mixed-effect model was fitted to characterize the association between the distance and incidence rates of thyroid cancer, adjusting for the potential confounding variables.

## Results

*The location of nuclear power plants and thyroid cancer incidence rate*

Map 1 shows the location of nuclear power plants in U.S. and incidence rates of thyroid cancer by county level in 2004-2008. The most elevated thyroid cancer rates in U.S. were localized in areas with high concentration of nuclear power plants, most of which were in the Northeast. Although two nuclear power plants were located in Minnesota and one nuclear power plant was located in Kansas, incidence rates of thyroid cancer by county level were not available because of state legislation and regulations which prohibited the release of county-level data to outside entities.  No nuclear power plant was located in Hawaii and Alaska.

*The area of nuclear power plants and trend of incidence rates of thyroid cancer for distance from nuclear power plant*

Table 2 shows that the incidence rates of thyroid cancer for each area.

Map 2 and Table 2 show the number and region of area from the nearest nuclear power plants. Area 15, 22, 23, 24, 26, and 29 included 2, Area 27 and 28 included 3, Area 14 included 6, Area 25 included 7, and Area 19 included 10 45-mile zones from the nearest nuclear power plant. Because of overlap of the zones from nuclear power plants, these were combined to avoid double counting. Area 17 and 30 were located in Kansas and Minnesota, where incidence rates of thyroid cancer by county level were not available. Area 5 includes Waterford and River Bend nuclear plant in Louisiana and Grand Gulf nuclear plant in Mississippi. Because of the impact on Louisiana's population for the July – December 2005 time period due to Hurricanes Katrina/Rita, SEER excluded Louisiana cases diagnosed for that six month time period. The count was suppressed due to data consistency issue.

The U.S. Nuclear Regulatory Commission (NRC) has four regions in the U.S.  The NRC Region I was the Northeastern U.S. and consisted of 17 nuclear power plants. Region II was the Southeastern U.S. and consisted of 19 nuclear power plants. Region III was the northern Midwestern U.S. and consisted of 16 nuclear power plants. Region IV was the southern Midwestern and the Western U.S. and consisted of 14 nuclear power plants (Map 2).

Graph 1-4 shows the incidence rates of thyroid cancer in < 15 mile, 15 ~ < 30 mile, and 30 ~ < 45 mile zones from the nearest nuclear power plants for Region 1-4. These dependent variables were crude incidence rates per 100,000 person-year in 2004-2008. Red lines for Graphs 1-4 are age-adjusted incidence rate per 100,000 person-year in 2004-2008 in U.S.

Most of the incidence rates in Region I (Graph 1) were over the U.S. rate, which is 11.0 per 100,000 person-year. In Region2 (Graph 2), Area 3,4,10, and 14 were below the U.S. rate. In Region3 (Graph 3), Area 25 and 23 were over the U.S. rate. In Region4 (Graph 4), Area 8 exceeded the U.S. rate.

*Mixed-effect model for distance from the nearest nuclear power plant and incidence rates for thyroid cancer*

The incidence rate of thyroid cancer in a zone was the dependent variable and distance (mile zone) from the nearest nuclear power plant was the primary predicting variable. Other covariate factors are percentage of white people, females people, below poverty people, people over age 65, people under age 17, unemployed people and college graduates in the population within each zone. Total number of reactors and the longest length of operation of nuclear power plants within each area are also included as covariate factors. Percentage of white persons in the population within < 15 mile, 15 ~ < 30 mile, and 30 ~ < 45 mile zones from the nearest nuclear power plants was 55.3- 93.9%, female was

43.9- 63.2%, below poverty was 8.2- 22.1%, over age 65 was 7.5- 29.3%, under age 17 was 16.4- 31.7%, college graduates was 11.9- 38.0%, and unemployed was 2.3- 7.0%. Total number of reactors within the area was from 1-17, and the longest length of operation of nuclear power plants within the area was 10-30 years (Table 2).

As a baseline mixed-effect model, incidence rates of thyroid cancer of various areas were analyzed by distance (mile zone) from the nearest nuclear power plant for each area. Each area has its own random regression line such that the distribution of intercepts is following N(10.9, 30.3) and that of slopes on distance(mile zone) is following N(0.02,0.01) (Table 3). This baseline model showed that incidence rate of thyroid cancer of each zone was not associated to distance from the nearest nuclear power plant. The intercept was 10.9, which was the almost same as the U.S. average.

Other covariates were tested whether they contributed to the baseline model and the results are summarized in Table 4. College graduates ($p < 0.001$) and White ($p = 0.003$) had a significant association with incidence rates of thyroid cancer.

Based on the result (Table 4), college graduates ($p < 0.001$) were selected, and other variables were eliminated using backward elimination ($p > 0.05$). Distance (mile zone) from the nearest nuclear power plant was the primary variable, so distance and college graduates were in the model.

The results for the final mixed-effect model were found in Table 5. Each area has its own random regression line such that the distribution of intercepts is following N(3.9, 20.3) and that of slopes on distance(mile zone) is following N(-0.003, 0.01). Percent of college graduate persons in the population within each area is associated to incidence rate of thyroid cancer ( $\beta$ = 0.3 $p < 0.001$). After adjusting for percent of college graduates, the incidence rates of thyroid cancer was not associated with the distance (mile zone) from the nearest nuclear power plant ( $\beta$ ~N(-0.003, 0.01) $p = 0.872$). Table 6 shows estimated lines for each area. Seven of 30 areas had negative slope, which meant that the incidence rates of thyroid cancer was decreasing slightly with increasing distance from the nearest nuclear power plant. Over all; however, the incidence rates of thyroid cancer were not associated with the distance (mile zone) for each area.

## Discussion

An abundance of articles about the issue of cancer near nuclear power plants were published, but most of the studies focused on childhood cancer or examined mortality rates. This is the first study to look at the association between incidence rate of thyroid cancer and the distance (mile zone) from the nearest nuclear power plant all over the U.S.

The association observed may possibly be influenced by other factors, such as socio-economic status, education level, age distribution, and risk factors (i.e. white and female) for thyroid cancer. To assess this, these factors were handled as if they were confounding factors. Only education level, such as percentage of college graduation of persons in the population (age 25 and over), would be a confounder. Our study showed that there was no relation between the incidence rates of thyroid cancer and distance (mile zone) from the nearest nuclear power plant in the U.S. while controlling for other factors such as percentage of college graduates in the population within each zone.

Graph 1-4 show the association between the crude incidence rate of thyroid cancer and the distance (mile zone) from the nearest nuclear power plant. Interestingly, in Region1, where the highest concentration area of nuclear power plants exists in the U.S., most of the zones are over the U.S. average rate (red line) (Graph 1). The physicians in the northeastern area (Region I) may check patients' thyroids frequently and carefully because the area is the highest concentration of nuclear power plants in the U.S. This could lead to possible detection bias. Another possible explanation is that the use of medical radiation therapy could be higher in the northeastern area (Region I).

In Region4, where each nuclear power plant is widely separated, most rates are below the U.S. average rate (red line) (Graph 4).

Potential exposure to radioactive emission of nuclear power plants would also be influenced by other factors such as topography or weather conditions (wind, precipitation). Radiation exposure level data on air, soil, water, and food within each zone would be desirable; however, such data were not available. It was therefore decided to work with the distance (mile zone) from the nearest nuclear power plant, that is, proximity to the nearest nuclear power plant.

In general, the ionizing radiation exposure from a nuclear power plant in routine operation is small compared to the exposure due to other sources, such as medical imaging. Unlike the medical imaging, however, ionizing radiation exposure is widespread, not only individual level. Considering the lifetime of radiation is much longer than that of human beings, the risk associated with radiation is increasing by an accumulation of environmental radiation.

No attempt was made in this study to evaluate nonmalignant conditions of the thyroid gland that can result from ionizing radiation exposure. It is possible that there is a higher than expected incidence of autoimmune thyroiditis or benign thyroid nodules in the study population.

Finally, it is important to recognize that the incidence of thyroid cancer has been rising worldwide for the past few decades. The specific reasons for this are not entirely clear but may include increased exposure to radiation from a wide variety of sources (nuclear fallout, medical sources, increased background radiation), changes in pathologic criteria defining malignancy, and increased screening and early diagnosis. Any attempt to prove a causal link between a low-level radiation exposure and the development of thyroid cancer will be hampered by this trend.

## Limitations

This study had several limitations. This was a cross-sectional and ecological study, so association among groups may not hold at the individual levels; thus, there is a possibility of making an ecological fallacy.

We didn't consider ionizing radiation exposure levels, so it was difficult to show a biological plausibility between exposure (proximate to a nuclear power plant) and outcome (thyroid cancer incidence).

We assumed that population and thyroid cancer incidence cases from 2004-2008 distributed constantly in a county, and estimated crude incidence rates of thyroid cancer at 15 mile intervals from the nearest nuclear power plant using ArcGIS, since the national cancer registry database was not available at the individual level.

The residential history of the persons was not available. Persons who lived in particular counties at the time of diagnosis may not have been long-term residents. Some residents could have moved elsewhere and been diagnosed in another part of the country. We didn’t include other facilities, which had potential radioactive emission. These could lead to possible misclassification bias.

## Future Study

Future studies should make all due effort to establishing ionizing radiation exposure levels, by county or smaller block (e.g. census tract), and investigating multiple vectors of ingestion (air, water, food) and the combination of local and distant sources of ionizing radiation. The Department of Energy (DOE) National Laboratories and Technology centers, shut down reactors, DOE/non-DOE research reactors, and radioactive waste facilities should be included. Age-adjusted incidence rates for each mile zone should be calculated in future studies.

The ideal study method is a cohort study for a long period by individual level, including residential history, ionizing radiation exposure level, and medical history.

Many of nuclear power plants in Japan are grouped together in cluster of three or four. The 15 nuclear power reactors around western Honshu's Wakasa Bay is the highest concentration of nuclear power plants in the world. Following up for people who live in Wakasa Bay for a long time would be good for understanding the health effects of nuclear power plants.

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**Figure 1: Illustration of Three 15 mile Interval Zones from a Nuclear Power Plant and Combined Zones.**

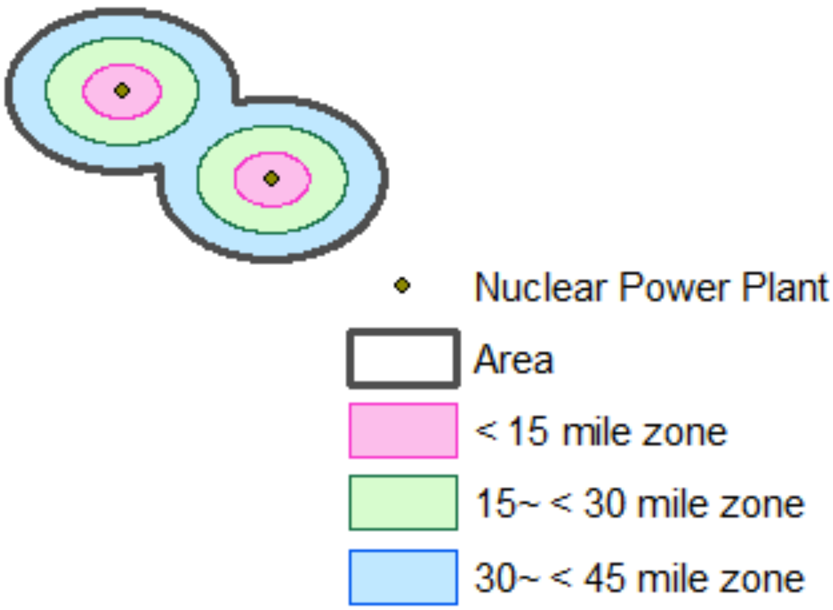
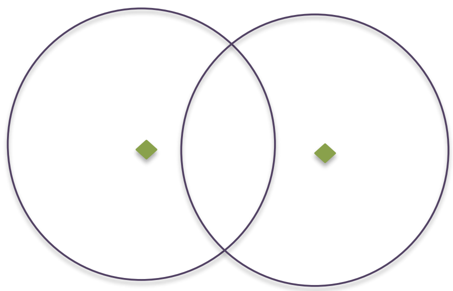
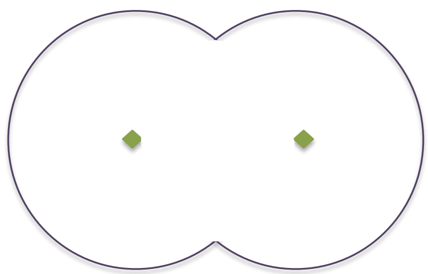


**Figure 2: Steps for Calculating Incidence Rates of Thyroid Cancer in the Study Zones.**

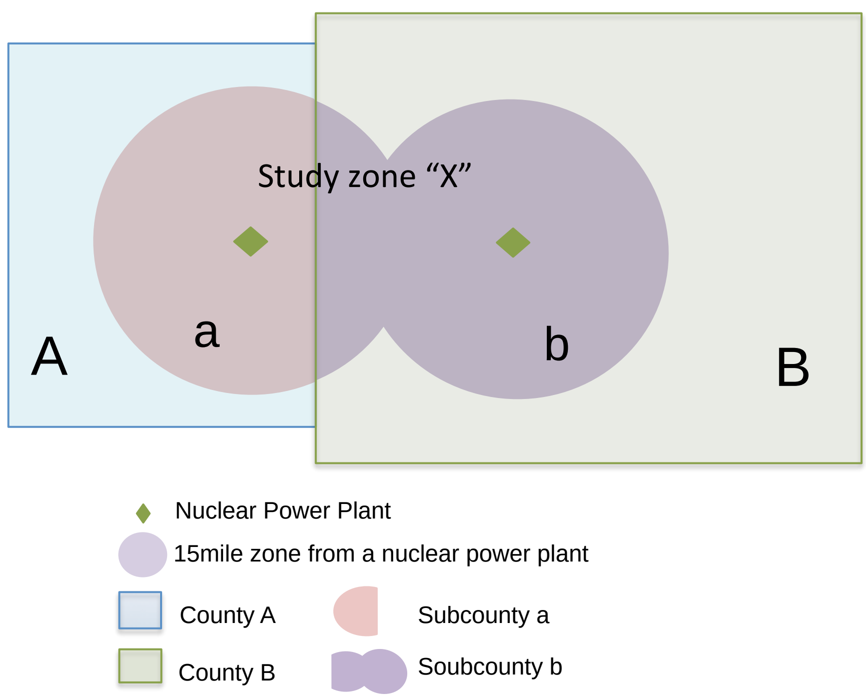
1. Distance from a nuclear power plant was calculated.



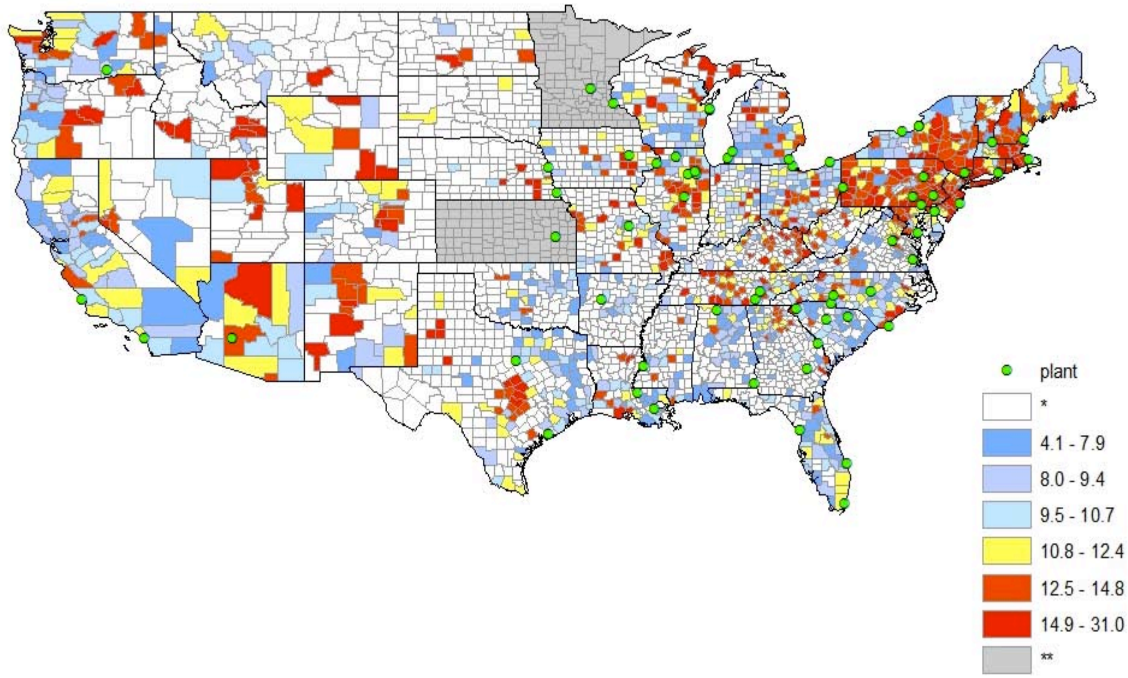
2. Dissolve



3. Intersect

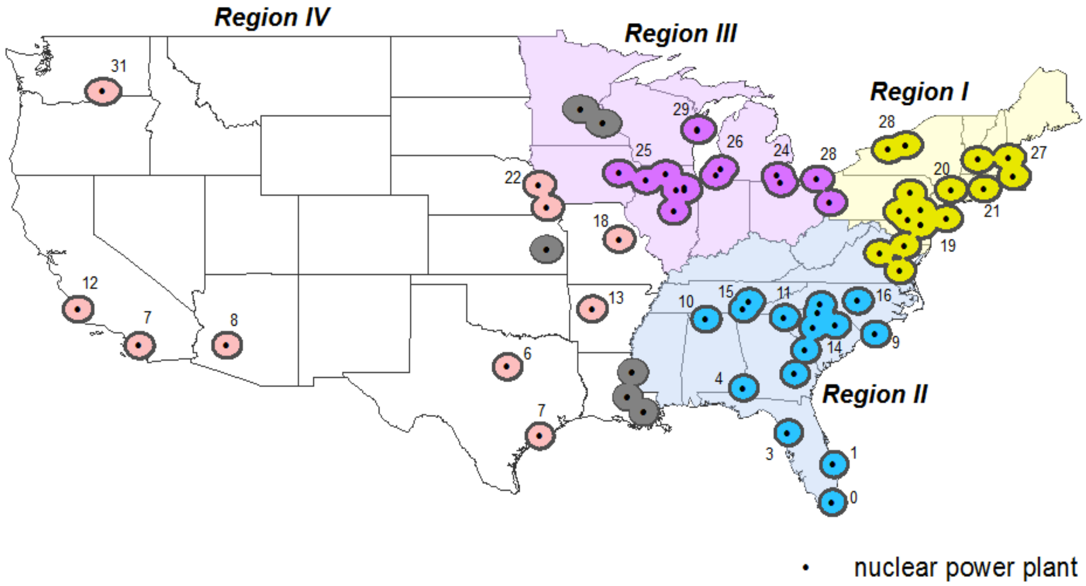


**Map 1: Thyroid Cancer Incidence Rates*** by County 2004-2008**
(All Races, Both Sexes, All Ages)



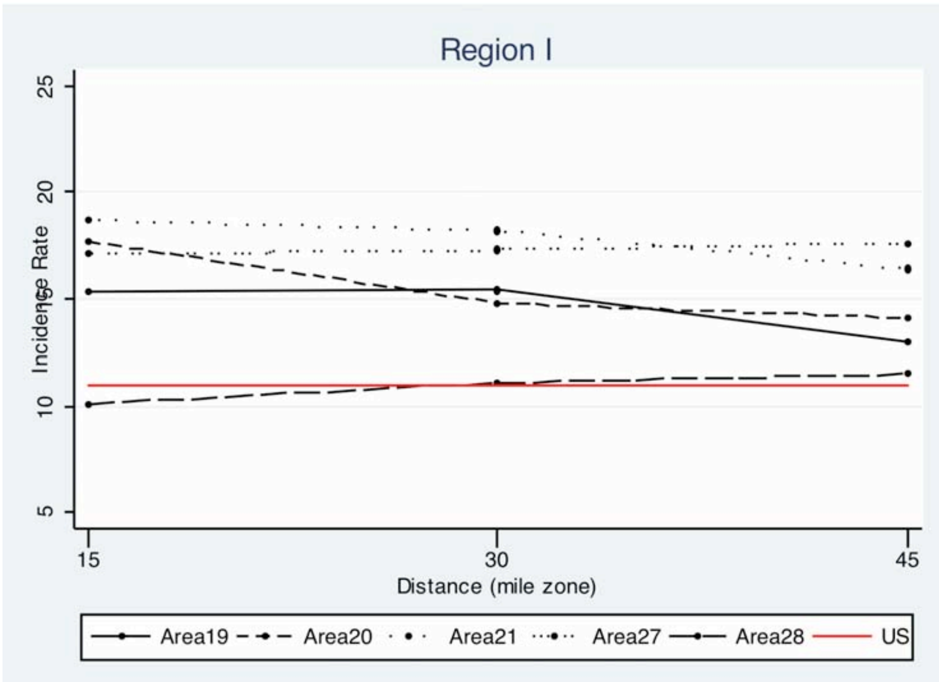

* Data have been suppressed to ensure confidentiality and stability of rate estimates. Counts are suppressed if fewer than 16 cases were reported in a specific area-sex-case category.
** Data not available because of state legislation and regulations which prohibit the release of county level data to outside entities.
***Incidence Rates (Cases per 100,000 population per year) are age-adjusted to the 2000 US standard population.
Source : CDC's National Program of Cancer Registries Cancer Surveillance System (NRCP-CSS) November 2010 data submission, SEER November 2010 submission and State Cancer Registry

**Map 2: Regions and Areas of Combined 45-mile Zones from a Nuclear Power Plant**



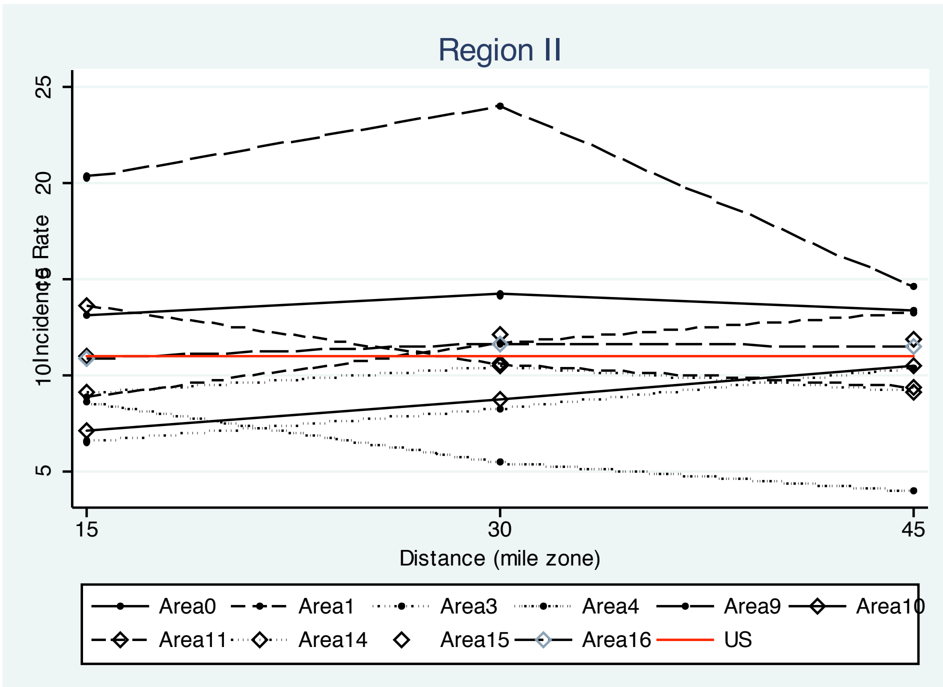

* Gray areas: Incidence rates and average cases are not available.

**Graph 1: The Association between Crude incidence Rates of Thyroid Cancer and Distance from the Nearest Nuclear Power Plants in Region 1**



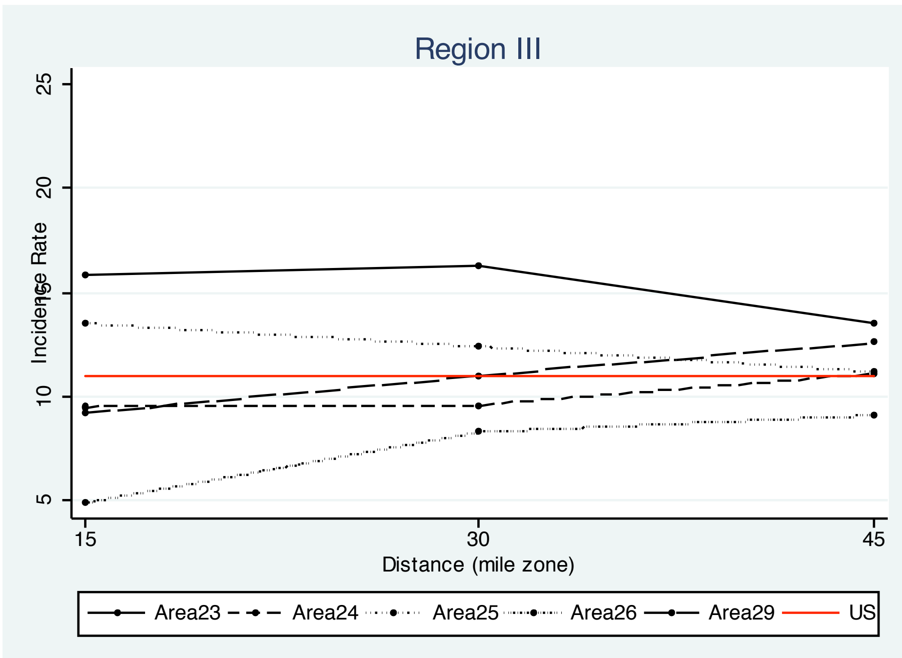

* Distance (mile zone) : 15: < 15 mile zone
30: 15~ < 30 mile zone
45: 30~ < 45 mile zone

**Graph 2: The Association between Crude incidence Rates of Thyroid Cancer and Distance from the Nearest Nuclear Power Plants in Region 2**



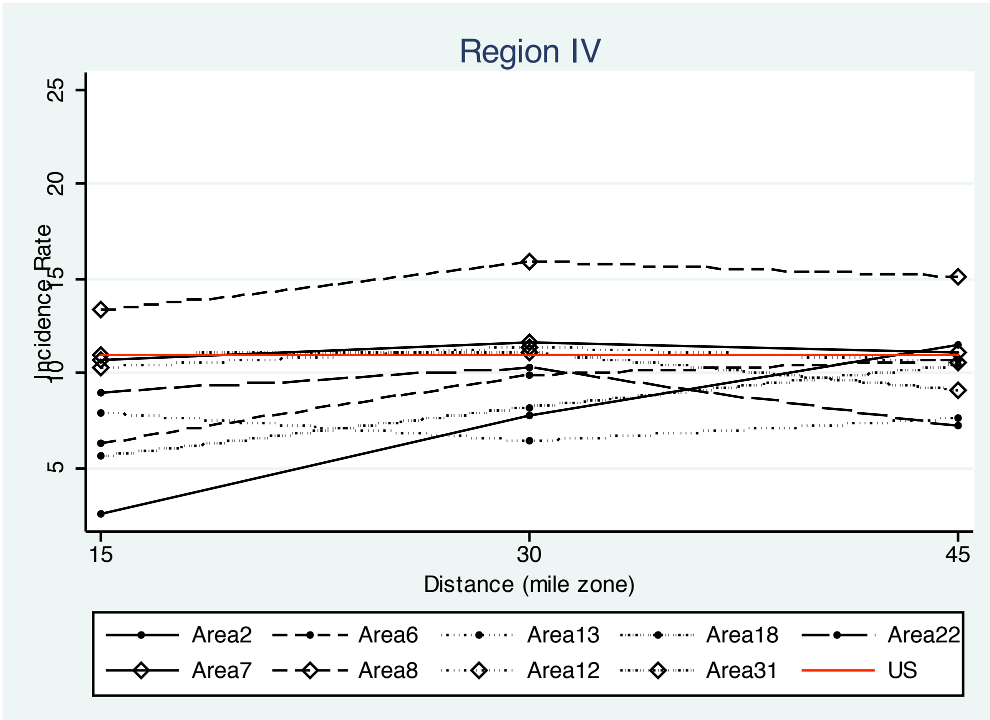

* Distance (mile zone) : 15: < 15 mile zone
30: 15~ < 30 mile zone
45: 30~ <45 mile zone

**Graph 3: The Association between Crude incidence Rates of Thyroid Cancer and Distance from the Nearest Nuclear Power Plants in Region 3**




* Distance (mile zone) : 15: < 15 mile zone
30: 15~ < 30 mile zone
45: 30~ < 45 mile zone

**Graph 4: The Association between Crude incidence Rates of Thyroid Cancer and Distance from the Nearest Nuclear Power Plants in Region 4**




* Distance (mile zone) : 15: < 15 mile zone
30: 15~ < 30 mile zone
45: 30~ < 45 mile zone

**Table 1: Potential Confounding Variables, for the Thyroid Cancer Incidence in 2004-2008 and Distance from Nuclear Power Plants Study**

| Variable | Definition | Type of variable | Possible response |
|---|---|---|---|
| **Demographics** | | | |
| Population 65+ | Percent of people 65+ | Integer | N/A |
| Population 17- | Percent of people 17- | Integer | N/A |
| Gender | Percent of females people | Integer | N/A |
| Race | Percent of white people | Integer | N/A |
| Unemployed | Percent of persons unemployed (age 16-64) | Integer | N/A |
| College graduates | Percent of college graduates (age 25 and over) | Integer | N/A |
| Below Poverty | Percent of below poverty people | Integer | N/A |
| **Nuclear Power Plants** | | | |
| Length | Years of reactor operation | Categorical | 1. 10-19 years<br>2. 20-29 years<br>3. 30-39 years |
| Number of reactors | | Integer | N/A |

## Table 2: Total Number of Reactors and Length of Nuclear Power Plants and Selected Characteristics of Areas, for the Thyroid Cancer Incidence in 2004-2008 and Distance from Nuclear Power Plants Study

| | | | | | | | | Percentages (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | Nuclear Power Plant | State | Total no. of reactors | Length* (yrs) | Distance from plants ( mil zone) | Incidence Rate** | Total Population 2000 | White | Female | Below poverty | >65 y | <17y | College Grad | Unemployd |
| 0 | Turkey Point | FL | 2 | 30 | <15 | 13.1 | 415106 | 65.9 | 48.7 | 20.3 | 12.6 | 23.4 | 20.5 | 4.0 |
| | | | | | 15~ <30 | 14.2 | 1029810 | 71.3 | 48.7 | 20.3 | 13.6 | 25.4 | 22.2 | 4.3 |
| | | | | | 30~ <45 | 13.4 | 1147883 | 70.6 | 55.2 | 18.4 | 14.2 | 24.2 | 22.6 | 4.0 |
| 1 | St. Lucie | FL | 2 | 30 | <15 | 8.9 | 105748 | 71.2 | 45.2 | 16.8 | 20.7 | 19.5 | 14.7 | 4.8 |
| | | | | | 15~ <30 | 11.7 | 252349 | 87.8 | 46.0 | 14.7 | 26.6 | 21.8 | 22.1 | 5.0 |
| | | | | | 30~ <45 | 13.3 | 470454 | 81.5 | 55.4 | 14.5 | 23.8 | 21.0 | 25.7 | 3.6 |
| 2 | South Texas | TX | 2 | 10 | <15 | 2.5 | 21766 | 65.3 | 48.5 | 19.9 | 12.0 | 28.9 | 12.0 | 6.5 |
| | Project | | | | 15~ <30 | 7.7 | 57799 | 74.0 | 46.3 | 16.1 | 11.7 | 29.3 | 16.0 | 5.3 |
| | | | | | 30~ <45 | 11.5 | 197468 | 70.3 | 50.6 | 12.8 | 9.1 | 29.6 | 23.2 | 4.4 |
| 3 | Crystal River | FL | 1 | 30 | <15 | 6.6 | 54967 | 86.1 | 47.6 | 18.1 | 28.2 | 16.4 | 11.9 | 3.3 |
| | | | | | 15~ <30 | 8.3 | 160242 | 93.3 | 47.0 | 18.1 | 29.3 | 19.8 | 13.3 | 4.5 |
| | | | | | 30~ <45 | 10.4 | 333858 | 88.0 | 54.5 | 17.6 | 25.6 | 19.9 | 14.8 | 4.6 |
| 4 | Joseph M. | AL | 2 | 30 | <15 | 8.6 | 61221 | 68.6 | 51.1 | 18.9 | 13.7 | 25.4 | 17.1 | 3.7 |
| | Farley | | | | 15~ <30 | 5.5 | 104014 | 70.2 | 49.7 | 20.3 | 14.7 | 25.7 | 14.6 | 4.4 |
| | | | | | 30~ <45 | 4.0 | 148440 | 65.8 | 51.8 | 22.1 | 13.8 | 25.3 | 12.3 | 4.3 |
| 6 | Comanche Peak | TX | 2 | 10 | <15 | 6.3 | 56785 | 83.9 | 45.7 | 12.4 | 13.8 | 23.1 | 16.7 | 3.6 |
| | | | | | 15~ <30 | 9.9 | 216197 | 86.0 | 45.5 | 13.9 | 11.0 | 28.2 | 20.8 | 3.8 |
| | | | | | 30~ <45 | 10.7 | 772075 | 74.9 | 52.1 | 14.4 | 9.2 | 27.9 | 24.5 | 3.7 |
| 7 | San Onofre | CA | 2 | 20 | <15 | 10.7 | 607144 | 61.8 | 47.4 | 12.9 | 9.7 | 25.3 | 28.7 | 4.1 |
| | | | | | 15~ <30 | 11.6 | 1583511 | 66.5 | 47.3 | 12.8 | 10.4 | 27.5 | 30.5 | 4.5 |
| | | | | | 30~ <45 | 11.1 | 1924084 | 64.3 | 53.3 | 13.6 | 10.4 | 27.1 | 28.7 | 4.8 |
| 8 | Palo Verde | AZ | 2 | 20 | <15 | 13.3 | 269086 | 67.9 | 43.9 | 16.6 | 10.3 | 23.7 | 22.7 | 5.6 |
| | | | | | 15~ <30 | 15.9 | 659005 | 81.2 | 43.9 | 16.6 | 12.3 | 28.3 | 27.2 | 6.7 |
| | | | | | 30~ <45 | 15.1 | 873293 | 77.2 | 56.5 | 16.7 | 11.8 | 27.0 | 25.6 | 6.4 |
| 9 | Brunswick | NC | 2 | 20 | <15 | 20.3 | 49412 | 71.7 | 45.2 | 17.2 | 13.3 | 18.6 | 20.3 | 3.7 |
| | | | | | 15~ <30 | 24.0 | 182925 | 82.4 | 47.0 | 18.0 | 14.2 | 21.9 | 27.6 | 4.2 |
| | | | | | 30~ <45 | 14.6 | 90974 | 72.0 | 63.2 | 20.6 | 14.3 | 23.4 | 14.4 | 5.1 |
| 10 | Browns Ferry | AL | 3 | 30 | <15 | 7.2 | 70770 | 81.8 | 49.2 | 15.1 | 11.7 | 24.5 | 15.5 | 3.7 |
| | | | | | 15~ <30 | 8.8 | 271792 | 81.1 | 50.2 | 14.9 | 12.4 | 25.1 | 22.0 | 3.8 |
| | | | | | 30~ <45 | 10.5 | 396756 | 82.9 | 52.0 | 15.9 | 12.9 | 24.9 | 22.1 | 4.2 |
| 11 | Oconee | SC | 2 | 30 | <15 | 13.6 | 113933 | 84.9 | 48.2 | 16.0 | 12.4 | 21.7 | 17.6 | 3.0 |
| | | | | | 15~ <30 | 10.6 | 352904 | 84.8 | 48.8 | 17.2 | 13.9 | 24.0 | 20.3 | 3.1 |
| | | | | | 30~ <45 | 9.4 | 579702 | 82.0 | 53.2 | 16.8 | 14.2 | 23.7 | 21.4 | 3.0 |
| 12 | Diablo Canyon | CA | 2 | 20 | <15 | 10.3 | 18374 | 79.5 | 45.7 | 14.3 | 13.6 | 20.3 | 25.1 | 6.6 |
| | | | | | 15~ <30 | 11.4 | 79579 | 83.9 | 46.2 | 14.8 | 14.4 | 22.5 | 27.5 | 6.4 |
| | | | | | 30~ <45 | 10.6 | 179712 | 77.7 | 50.6 | 15.8 | 13.4 | 23.5 | 27.4 | 5.2 |
| 13 | Arkansas | AR | 2 | 30 | <15 | 7.9 | 28843 | 87.8 | 48.2 | 18.5 | 13.2 | 24.4 | 14.7 | 4.5 |
| | | | | | 15~ <30 | 6.4 | 73741 | 93.9 | 48.6 | 18.4 | 14.6 | 26.0 | 14.5 | 5.1 |
| | | | | | 30~ <45 | 7.6 | 185674 | 87.2 | 52.2 | 17.6 | 15.2 | 24.5 | 17.8 | 4.9 |
| 14 | Catawba | SC | 10 | 30 | <15 | 9.1 | 1070240 | 62.3 | 46.6 | 17.0 | 9.3 | 23.1 | 24.1 | 3.3 |
| | McGuire | NC | | | 15~ <30 | 10.5 | 1566080 | 73.1 | 48.0 | 18.6 | 12.0 | 27.3 | 21.5 | 4.1 |
| | V. C. Summer | SC | | | 30~ <45 | 9.2 | 1665088 | 69.4 | 57.1 | 19.2 | 11.8 | 25.9 | 17.4 | 3.9 |
| | Edwin I. Hatch | GA | | | | | | | | | | | | |
| | H. B. Robinson | SC | | | | | | | | | | | | |
| | Vogtle | GA | | | | | | | | | | | | |
| 15 | Sequoyah | TN | 3 | 20 | <15 | 11.0 | 360116 | 79.7 | 50.7 | 16.7 | 13.3 | 22.8 | 20.0 | 3.6 |
| | Watts Bar | TN | | | 15~ <30 | 12.1 | 382038 | 92.8 | 48.7 | 17.7 | 13.8 | 24.6 | 14.8 | 4.1 |
| | | | | | 30~ <45 | 11.9 | 431246 | 92.9 | 54.0 | 18.0 | 13.5 | 23.9 | 14.5 | 4.2 |
| 16 | Shearon Harris | NC | 1 | 30 | <15 | 10.9 | 277335 | 62.9 | 43.9 | 12.9 | 7.5 | 21.8 | 33.4 | 2.3 |
| | | | | | 15~ <30 | 11.7 | 640442 | 72.1 | 45.4 | 15.3 | 9.8 | 25.8 | 38.0 | 3.0 |
| | | | | | 30~ <45 | 11.5 | 873758 | 68.1 | 56.9 | 16.7 | 10.3 | 24.9 | 27.6 | 3.3 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | Callaway | MO | 1 | 20 | <15 | 5.6 | 28296 | 89.0 | 46.2 | 13.7 | 11.7 | 24.3 | 14.2 | 2.8 |
| | | | | | 15~ <30 | 8.2 | 125196 | 91.6 | 47.8 | 15.1 | 12.0 | 24.8 | 24.7 | 2.7 |
| | | | | | 30~ <45 | 10.4 | 264594 | 91.0 | 52.0 | 15.2 | 11.5 | 24.9 | 25.0 | 2.7 |
| 19 | Hope Creek | NJ | 17 | 30 | <15 | 15.3 | 2750432 | 80.5 | 48.9 | 9.8 | 13.6 | 23.8 | 25.1 | 3.2 |
| | Salem | NJ | | | 15~ <30 | 15.4 | 7011639 | 77.8 | 50.2 | 12.0 | 14.0 | 25.0 | 25.1 | 3.8 |
| | Calvert Cliffs | MD | | | 30~ <45 | 13.0 | 8788774 | 66.2 | 53.7 | 12.8 | 12.5 | 25.0 | 26.7 | 3.6 |
| | Limerick | PA | | | | | | | | | | | | |
| | Peach Bottom | PA | | | | | | | | | | | | |
| | North Anna | VA | | | | | | | | | | | | |
| | Oyster Creek | NJ | | | | | | | | | | | | |
| | Surry | VA | | | | | | | | | | | | |
| | Susquehanna | PA | | | | | | | | | | | | |
| | Three Mile Island | PA | | | | | | | | | | | | |
| 20 | Indian Point | NY | 3 | 30 | <15 | 17.7 | 827048 | 73.3 | 50.1 | 9.9 | 12.4 | 25.6 | 36.7 | 3.2 |
| | | | | | 15~ <30 | 14.8 | 3807324 | 62.6 | 51.0 | 15.4 | 12.5 | 25.5 | 31.2 | 4.5 |
| | | | | | 30~ <45 | 14.1 | 9557012 | 55.3 | 52.7 | 15.5 | 12.4 | 24.1 | 29.6 | 4.8 |
| 21 | Millstone | CT | 3 | 30 | <15 | 18.7 | 146500 | 85.2 | 49.3 | 8.6 | 12.7 | 23.7 | 26.5 | 2.4 |
| | | | | | 15~ <30 | 18.2 | 752181 | 86.7 | 49.5 | 8.2 | 12.9 | 24.9 | 28.9 | 2.7 |
| | | | | | 30~ <45 | 16.4 | 1624864 | 83.1 | 52.5 | 10.5 | 13.6 | 24.6 | 27.5 | 2.7 |
| 22 | Cooper Station | NE | 2 | 30 | <15 | 9.0 | 172105 | 81.7 | 49.2 | 13.7 | 11.6 | 25.5 | 26.9 | 2.9 |
| | Fort Calhoun | NE | | | 15~ <30 | 10.3 | 517283 | 86.5 | 48.8 | 13.0 | 11.8 | 27.2 | 27.7 | 2.9 |
| | | | | | 30~ <45 | 7.2 | 253552 | 88.6 | 56.3 | 11.0 | 14.0 | 26.5 | 19.7 | 2.8 |
| 23 | Beaver Valley | PA | 3 | 30 | <15 | 15.8 | 523682 | 93.3 | 52.3 | 12.5 | 16.6 | 23.4 | 20.2 | 4.0 |
| | Perry | OH | | | 15~ <30 | 16.3 | 1621913 | 84.7 | 53.0 | 14.0 | 16.7 | 23.3 | 23.2 | 4.3 |
| | | | | | 30~ <45 | 13.5 | 2621703 | 82.6 | 51.7 | 15.4 | 16.2 | 23.8 | 22.4 | 4.4 |
| 24 | Davis-Besse | OH | 2 | 30 | <15 | 9.5 | 430854 | 65.0 | 51.6 | 20.3 | 12.4 | 27.3 | 16.9 | 4.2 |
| | Fermi | MI | | | 15~ <30 | 9.6 | 1731530 | 61.4 | 51.9 | 21.5 | 12.1 | 27.3 | 18.7 | 4.2 |
| | | | | | 30~ <45 | 11.1 | 1843862 | 74.9 | 51.2 | 16.6 | 11.9 | 25.8 | 25.8 | 3.7 |
| 25 | Braidwood | IL | 12 | 30 | <15 | 13.5 | 793716 | 82.2 | 47.2 | 11.1 | 11.1 | 25.1 | 20.2 | 3.7 |
| | Dresden | IL | | | 15~ <30 | 12.4 | 2389232 | 81.0 | 49.0 | 13.3 | 12.0 | 26.8 | 26.6 | 4.2 |
| | LaSalle | IL | | | 30~ <45 | 11.2 | 5119333 | 70.0 | 52.6 | 14.3 | 11.7 | 26.2 | 27.9 | 4.3 |
| | Byron | IL | | | | | | | | | | | | |
| | Quad Cities | IL | | | | | | | | | | | | |
| | Clinton | IL | | | | | | | | | | | | |
| | Duane Arnold | IA | | | | | | | | | | | | |
| 26 | Donald C. Cook | MI | 3 | 30 | <15 | 4.9 | 168219 | 81.1 | 50.9 | 17.0 | 13.8 | 26.3 | 18.4 | 3.8 |
| | Palisades | MI | | | 15~ <30 | 8.3 | 359231 | 85.8 | 49.8 | 16.0 | 13.1 | 26.3 | 19.1 | 3.3 |
| | | | | | 30~ <45 | 9.1 | 717894 | 87.8 | 51.4 | 15.7 | 11.8 | 26.5 | 22.1 | 2.9 |
| 27 | Pilgrim | MA | 3 | 30 | <15 | 17.1 | 642190 | 87.2 | 49.8 | 9.0 | 12.3 | 24.8 | 29.0 | 2.7 |
| | Seabrook | NH | | | 15~ <30 | 17.3 | 1981281 | 91.4 | 50.2 | 9.8 | 13.9 | 24.8 | 31.1 | 2.9 |
| | Vermont Yankee | VT | | | 30~ <45 | 17.6 | 3956736 | 83.6 | 52.7 | 12.1 | 13.1 | 23.1 | 33.6 | 2.8 |
| 28 | Ginna | NY | 4 | 30 | <15 | 10.1 | 187944 | 84.3 | 50.5 | 14.7 | 12.3 | 25.8 | 24.7 | 3.8 |
| | James A. Fitzpatric | NY | | | 15~ <30 | 11.1 | 786978 | 84.4 | 50.8 | 14.4 | 13.0 | 25.9 | 27.2 | 3.7 |
| | Nine Mile Point | NY | | | 30~ <45 | 11.5 | 694224 | 87.0 | 52.2 | 14.0 | 13.6 | 25.5 | 24.7 | 3.8 |
| 29 | Kewaunee | WI | 3 | 30 | <15 | 9.2 | 54177 | 92.7 | 48.9 | 10.9 | 14.0 | 25.0 | 15.9 | 2.9 |
| | Point Beach | WI | | | 15~ <30 | 11.0 | 217482 | 93.4 | 48.1 | 10.5 | 12.3 | 26.0 | 20.6 | 2.9 |
| | | | | | 30~ <45 | 12.6 | 266281 | 93.7 | 52.2 | 9.5 | 12.2 | 26.5 | 20.5 | 2.8 |
| 31 | Columbia | WA | 1 | 20 | <15 | 11.0 | 60780 | 79.6 | 46.5 | 12.9 | 9.5 | 27.6 | 24.2 | 4.6 |
| | | | | | 15~ <30 | 11.1 | 120234 | 82.9 | 46.4 | 15.5 | 10.7 | 31.7 | 23.5 | 5.9 |
| | | | | | 30~ <45 | 9.1 | 106747 | 72.1 | 55.2 | 19.9 | 11.4 | 30.6 | 16.2 | 7.0 |

* Longest length of nuclear power plants within each area

** Crude incidence rates of thyroid cancer per 100,000 person-year in 2004-2008

**Table 3: Baseline Mixed-Effect Model, for the Thyroid Cancer Incidence in 2004-2008 and Distance from Nuclear Power Plants**

| **Ramdom effects:** | StdDev |
|---:|---:|
| intercept | 5.5 |
| distance | 0.1 |

| **Fixed effects:** | **β** | **Std. Err.** | **p-value** |
|---:|---:|---:|---:|
| intercept | 10.9 | 1.1 | |
| distance | 0.02 | 0.02 | 0.440 |

**Table 4: Analysis Results, for the Thyroid Cancer Incidence in 2004-2008 and Distance from Nuclear Power Plants Study**

| Random effects: | StdDev | | |
|---|---|---|---|
| intercept | 4.5 | | |
| distance | 0.1 | | |
| **Fixed effects:** | **β** | **Std.Err.** | **p-value** |
| intercept | 0.1 | 6.6 | |
| distance | 0.002 | 0.02 | 0.992 |
| **White (%):** | 0.1 | 0.05 | 0.003 |
| **Female (%):** | 0.04 | 0.05 | 0.565 |
| **College Grad. (%):** | 0.3 | 0.1 | <0.001 |
| **Up age 65 (%):** | -0.2 | 0.1 | 0.113 |
| **Under age 17 (%)** | -0.2 | 0.2 | 0.203 |
| **Below poverty (%):** | -0.1 | 0.1 | 0.537 |
| **Unemployed (%):** | 0.4 | 0.5 | 0.345 |
| **Total no. of rectors:** | 0.06 | 0.2 | 0.755 |
| **Length (yrs):** | | | |
| 20-29 vs 10-19 | -0.5 | 2.5 | 0.833 |
| 30-39 vs 10-19 | -1.3 | 2.3 | 0.590 |

**Table 5: Multivariate Mixed-Effect Model, for the Thyroid Cancer Incidence in 2004-2008 and Distance from Nuclear Power Plants Study**

| Random effects: | StdDev |
|---|---|
| intercept | 4.5 |
| distance | 0.1 |

| Fixed effects: | β | Std.Err. | p-value |
|---|---|---|---|
| intercept | 3.9 | 1.3 | |
| distance | -0.003 | 0.02 | 0.872 |
| **College Grad. (%):** | 0.3 | 0.04 | <0.001 |

**Table 6: Estimated Lines for Each Area, for the Thyroid Cancer Incidence in 2004-2008 and Distance from Nuclear Power Plants Study**

| Area | slope | intercept |
|---|---|---|
| **0** | 0.0 | 2.8 |
| **1** | 0.0 | 0.0 |
| **2** | 0.1 | -6.3 |
| **3** | 0.1 | -1.9 |
| **4** | -0.1 | -1.0 |
| **6** | 0.0 | -3.3 |
| **7** | 0.0 | -3.2 |
| **8** | 0.0 | 2.0 |
| **9** | -0.1 | 12.2 |
| **10** | 0.0 | -2.7 |
| **11** | -0.1 | 4.5 |
| **12** | 0.0 | -2.0 |
| **13** | 0.0 | -1.1 |
| **14** | 0.1 | -3.1 |
| **15** | 0.1 | 0.5 |

| Area | slope | intercept |
|---|---|---|
| **16** | 0.1 | -5.8 |
| **18** | 0.0 | -4.1 |
| **19** | -0.1 | 4.2 |
| **20** | 0.0 | 1.6 |
| **21** | -0.1 | 6.8 |
| **22** | 0.0 | -4.2 |
| **23** | -0.1 | 6.4 |
| **24** | 0.0 | 0.2 |
| **25** | -0.1 | 3.5 |
| **26** | 0.1 | -5.5 |
| **27** | 0.0 | 3.9 |
| **28** | 0.0 | -2.7 |
| **29** | 0.0 | -0.6 |
| **31** | 0.0 | -1.3 |