INDOOR-SURVEYS, RADON POTENTIAL MAPS AND THEIR IMPACTS ON RADON AWARENESS IN CALIFORNIA

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Abstract

California radon surveys conducted between 1979 and 1990 found only small percentages of residences having indoor-radon concentrations exceeding 4 pCi/L. They established the perspective that indoor-radon is not a significant health issue in California, limiting interest in radon among many government agencies and citizens. Recent radon potential maps by the California Geological Survey show that higher radon potential areas, not detected by the early surveys, do exist within some California counties. Availability of these maps on the web has facilitated their use by consultants in Phase 1 environment assessments, in real estate disclosure and by the public; increasing the visibility of radon as an environmental health issue in California. One county recently began requiring radon map review during preparation of geotechnical reports for construction projects. This has resulted in consideration of radon at several sites and a commitment to radon resistant construction at a new fire station.

Introduction

The first goal of this paper is to discuss the origins and accuracy/inaccuracy of the pervasive perspective that California does not have significant radon problems. The second goal is to summarize how the California Geological Survey (CGS) and the California Department of Public Health (CDPH) have been working cooperatively to show that California does have local radon exposure issues by identifying and documenting the state's relatively small but significantly anomalous radon areas. The final goal of this paper is to show how CGS radon maps increasingly are being used, especially by consultants required to address the radon exposure issue when preparing Phase 1 environmental reports for construction projects. A new interactive radon map on the CGS website makes it quick and easy for anyone to obtain radon potential information for an address or named geographic location (e.g., XYZ School) within a completed CGS radon potential map area.

The current CDPH-CGS cooperative work to produce radon potential maps began in 2003. Churchill (2012a) describes the map development process and provides details about the associated CDPH radon surveys. Briefly, CGS radon potential maps are developed using a geologic approach similar in part to those advocated by Carlisle and Azzouz (1993) and organizations such as the British Geological Survey (Appleton, 2013). CGS develops its maps using indoor-radon data from CDPH surveys, uranium geochemical data, soil permeability data

(1) California Geological Survey (CGS) radon activities are funded through an interagency agreement, by a portion of the California Department of Public Health (CDPH) State Indoor Radon Grant from U.S. EPA and CGS matching funds.

and geologic maps at 1:100,000 scale or larger. To date CDPH has completed 20 radon-screening surveys and CGS has completed 10 radon potential maps. CGS radon maps are advisory, not regulatory. Currently CGS has one radon map in review and one in progress as shown in Figure 1. Approximately 15 million Californians reside in areas with completed CGS radon potential maps.

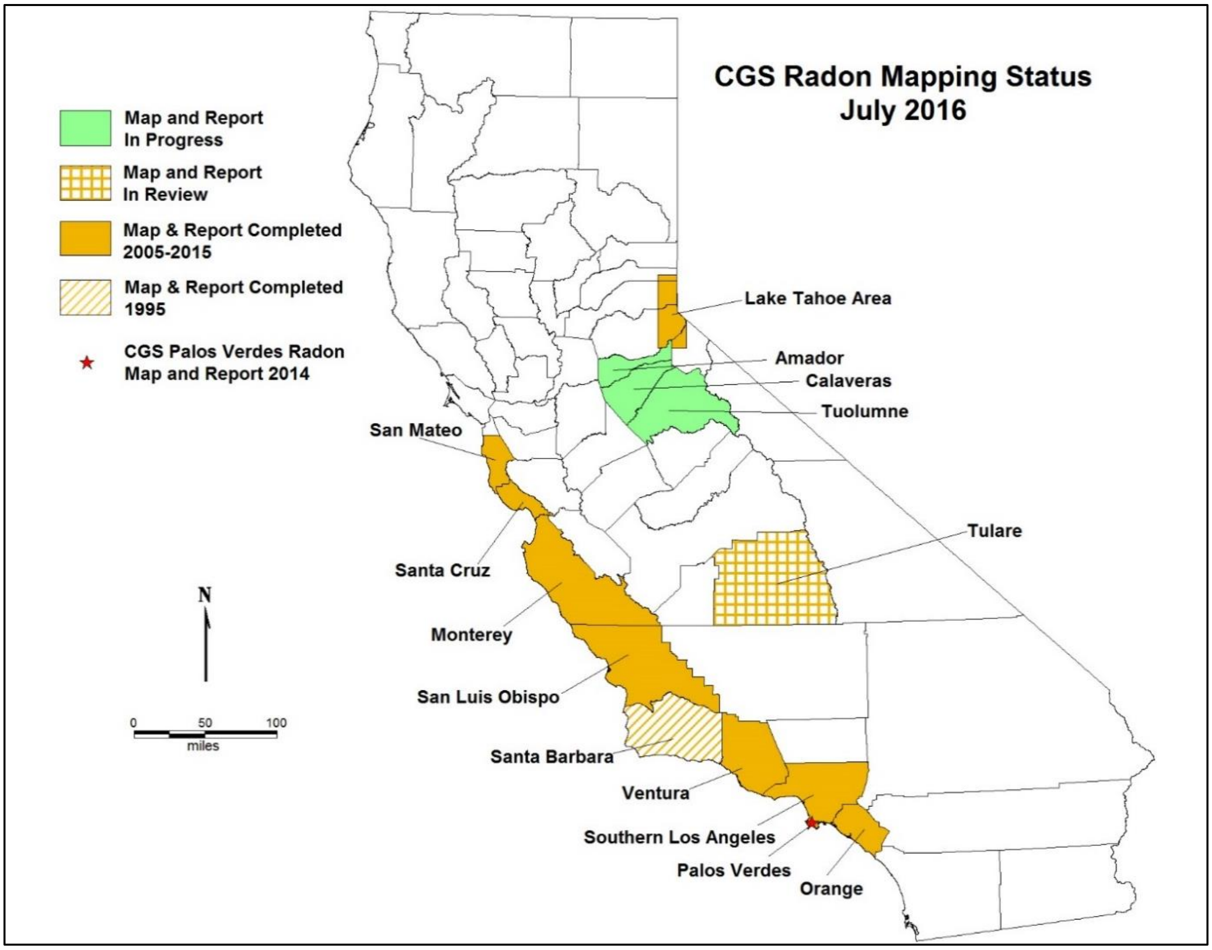

Figure (1): Status of CGS radon mapping as of July 2016

Historical Origins of California's Radon Perspective

California Radon Research and Media Reports—1979 to the mid-1990s

Since the 1990s, the dominant perspective among its citizens and health officials is that indoor radon is not a significant problem in California. A number of factors contributed to the development of this perspective including the type of radon surveys and their small numbers of samples, radon perspectives by state public health officials and radon researchers, and disagreements between radon experts reported by the media. Between 1979 and 1988, the California Department of Health Services (DHS) and Lawrence Berkeley Laboratory (LBL), along with other organizations, conducted a number of small, local radon surveys in California (see Figure 2). These surveys found either no homes or relatively few homes exceeding the U.S.

Environmental Protection Agency (EPA) recommended action level of 4 picoCuries per liter (pCi/L) radon (Kizer, 1989). At the same time, radon surveys of homes in the Midwest and Northeast were finding much higher percentages of homes exceeding 4 pCi/L. Most of these surveys occurred subsequent to the discovery of the 1984 Watras home in Pennsylvania, which dramatically increased national concern about indoor radon as a health issue in the United States (Brookins, 1990, p.7; Monmonier, 1997).

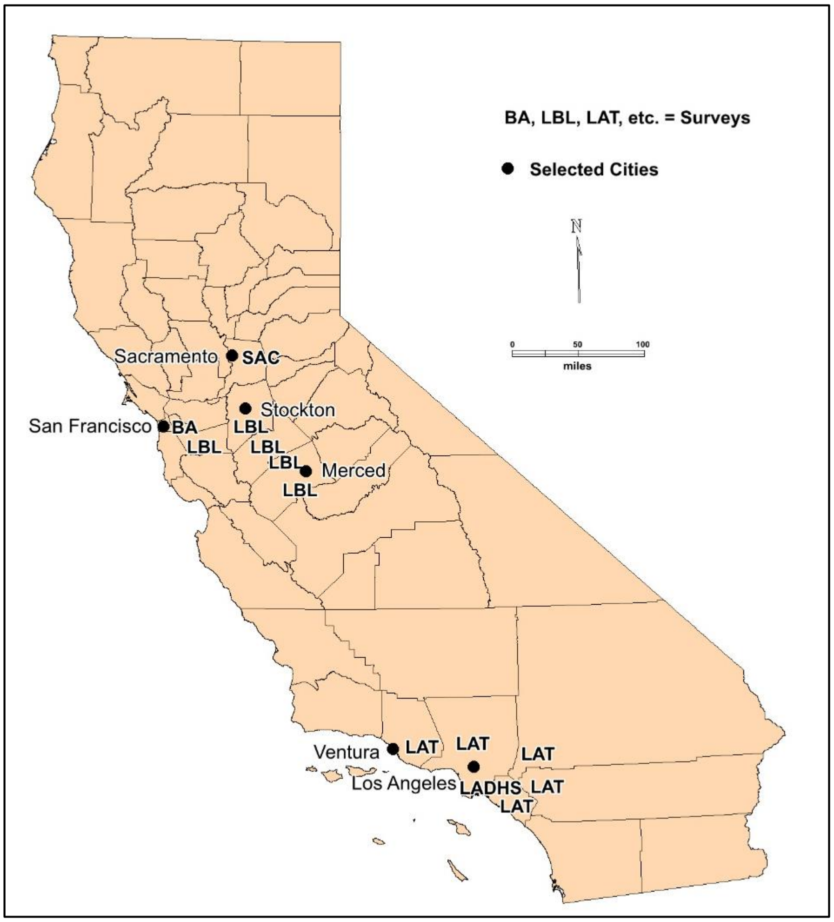

Figure (2): General locations of 1979 to 1988 California radon surveys

Surveys: BA = 1979 Bay Area survey by LBL, 29 homes; LBL = 1985 Alameda County and San Joaquin Valley survey by LBL, 55 homes total; LADHS 1986-87 survey by Los Angeles County Department of Health Services, 73 homes; LAT = Los Angeles Times Newspaper survey, 436 homes; SAC = 1988 survey, 100 homes by a local TV station (reference: Kizer, 1989)

Results from radon surveys in 17 states during 1987 and 1988 showed a significant percentage of homes exceeding 4 pCi/L, indicating that the indoor-radon problem in U.S. homes was far more widespread than previously thought. These survey results led to an EPA and Office of the Surgeon General advisory, issued on September 12, 1988, urging virtually every homeowner in the United States to test their house for radon (Stammer, 1988a). California was not one of the

17 states surveyed. DHS officials and LBL researchers immediately criticized the EPA call for testing all homes. As reported in the Los Angeles Times newspaper, DHS issued a statement that it could not endorse the EPA position for California. The Times quotes a DHS spokesman as saying "The state is not prepared to suggest that every homeowner have his home tested for radon…The state does encourage homeowners to learn as much as they can about radon, and we hope to assist with the publication of a booklet which is scheduled to come out in the next six months." The Times article noted that with this advisory the EPA was departing from its previous policy of suggesting radon testing only when homeowners believe they have a radon problem or live in a known radon "hot spot" area (Stammer, 1988a). DHS policy and LBL recommendations through the 1980s and 1990s remained consistent with the earlier EPA policy. Additionally, both DHS and LBL continued to insist that radon surveys needed to use yearlong measurements to be valid.

On September 14, 1988, a number of California newspapers reported the State Health Director's response to the EPA advisory. The Santa Cruz Sentinel Newspaper (Santa Cruz Sentinel, 1988) reported the Director as stating, "While we certainly agree with EPA that radon is a significant potential health problem, we do not believe at this time that every home in California should be tested for radon." The Director referenced the year-long-survey of 440 homes throughout California currently underway by the DHS and California Air Resources Board. He said he believed it would show radon is far less prevalent in California homes than in northeastern states with high-uranium soils, and pointed out that much of California enjoys a mild climate, its houses are well ventilated and built over crawlspaces rather than basements; all things making California homes less threatened by radon.

On October 2, 1988, the Los Angeles Times Newspaper reported the results of its yearlong radon survey of 436 Times employee homes in Los Angeles, Orange, Riverside, San Bernardino and Ventura Counties (Stammer, 1988b). The Times conducted the survey with technical assistance from the California DHS and others (Kizer, 1989). At this point, the Times study was the largest radon study in California. It found 1.2 percent of homes tested had indoor-radon concentrations above 4 pCi/L and most of these homes were in southern Ventura County. The highest radon concentration measured was 21.1 pCi/L. This finding prompted DHS to undertake a comprehensive yearlong study in 1989 of homes in eastern Ventura County and the southern San Fernando Valley portion of Los Angeles County. DHS reported the results of the study in September 1991 (Liu et al., 1991b). The study used alpha-track detectors exposed for one year from 862 residences to evaluate the radon potentials for 49 Zip Code areas in western Los Angeles and eastern Ventura counties. The measurements ranged from 0.1 to 15.9 pCi/L with a median of 1.2 pCi/L. Liu et al. (1991b) classified the Zip Code areas in high, medium, and low radon potential groups using radon data and geographic contiguity. Statistical analysis indicated that the average radon levels for the three Zip Code areas were significantly different from each other. The study-estimated percentages of homes exceeding 4 pCi/L radon are 14% for the high, 8% for the medium and 1% for the low region. The high radon potential region contains seven Zip Code areas, the medium 10 Zip Code areas and the low 32 Zip Code areas.

In March 1990 DHS published its survey of 310 (earlier reported as 440 by state officials) randomly selected homes statewide (Liu et al., 1990; Liu et al., 1991a; and Kizer et al., 1990).

This is the first radon survey to cover the entire state of California. Overall study conclusions were as quoted below:

- The annual geometric mean radon concentration in California is 0.85 pCi/L and a geometric standard deviation of 1.91.
- The approximate fractions of California population regularly exposed to residential radon concentrations greater than 4 pCi/L and 8 pCi/L is 0.8% and 0.03%, respectively. Currently (in 1990) there are approximately 11 million housing units in California so the expected number exceeding 4 pCi/L is 88,000, with lower and upper 95% confidence limits of 66,000 and 121,000 respectively.
- Indoor radon concentrations are found to be associated with geographic location, ventilation, type and age of residences and type of substructure. The Sierra Nevada foothills and Ventura County had higher concentrations than other areas of California.[2] The Sierra area, with approximately 220,000 residences, has the highest number of expected residences exceeding 4 pCi/L, approximately 54,000. The coastal area has the lowest expected number of residences exceeding 4 pCi/L, under less than 1,000 out of over 2,000,000.
- Residences whose windows/doors are rarely opened by occupants, structures with a full concrete slab, single-family houses, and new residences were found in general to have higher radon concentrations.

The authors included the following important qualifications to their conclusions, quoted in full here:

> "The fact that only a small percentage of California residences are expected to have annual average concentrations over 4 pCi/L does not imply that there is no radon problem in this state. Actually, the findings of elevated radon concentrations in the areas of the Sierra Foothills and Ventura/Los Angeles Counties indicate that there are some problem areas, which need further investigation. Finding these areas of elevated indoor radon was possibly fortuitous given the limited scope of the sampling (which was due in turn to the funding limitations), the geologic and climatic diversity of California, and the large variations in population density. In general, a survey of this size using a simple population-based sampling scheme would not have been expected to identify even a moderately-sized region of elevated indoor radon unless it also had a sufficiently high population to increase the probability of extensively sampling it."

The study recommended that a detailed study be undertaken to identify other areas with elevated indoor concentrations throughout the state. In addition, the authors recommended detailed studies to determine the extent of the problem area in any areas identified then or in the future as having elevated radon concentrations. Such a study was already underway in the Ventura County-Los Angeles County area. Except for follow-up work to confirm the Santa Barbara hot-

[2] *A simplified map showing the geographic subdivisions the authors used for California is available in Liu et al. (1991a).*

spot discovery described below, the Ventura–Los Angeles study previously described was the only detailed radon study conducted by DHS in the 1990s.

The Liu et al. (1990) study became the principle source of California indoor-radon information for state environmental and health agencies. More than any other study, it seems to have influenced these groups' radon views and policy. A Los Angeles Times article (Stammer, 1990) about the DHS study reported it confirmed earlier studies' findings that radon is present only in low levels in most California homes, and backed up the results of the Times' survey completed in October 1988. That article did note study findings that 10 to 15% of dwellings in the Ventura County region may surpass the EPA radon guideline. However, it concluded that the study findings bolstered California's contention that the EPA and U.S surgeon general overreacted in 1988 in urging that virtually every dwelling in the country be tested for radon. An LBL spokesperson was reported as saying that researchers have long believed that radon levels are fairly low in California, except in so-called hot spots (Stammer, 1990). The DHS study found such hot spots in the Sierra counties of Fresno, Mono, Tulare and Inyo; the radon annual geometric mean in those areas being 1.28 pCi/L compared to the statewide annual geometric mean of 0.85 pCi/L. The LBL spokesperson noted that in general most people shouldn't be concerned about radon in California but they should start to do something when any particular area has higher-than-average concentrations (Stammer, 1990).

In June and again in October 1990, Los Angeles County health officials and leaders of the American Lung Association (ALA) urged county homeowners to test their dwellings for radon, claiming that 50 to 100 county lives a year could be saved (Feldman, 1990; Lichtblau and Stammer, 1990). This recommendation was made after county review of radon data from various studies over the previous three years showed 2.2% of 1,860 homes tested exceed 4 pCi/L radon. In October, hoping to combat public apathy over radon, an "easily solvable problem," the county health officials released an estimate that 4.4% (75,000) Los Angeles county homes exceed 4 pCi/L radon. County health experts and the ALA noted that radon is a potent carcinogen and precautions should be taken because they are relatively inexpensive compared to the potential health risks (as little as $14 to test a home). In the June article, county toxics epidemiology program chief, Dr. Paul Papanek, Jr. is quoted as stating "Certainly if you look at the cost of things that we all do for safety—installing smoke detectors and putting seat belts on our families, this is at least as cost effective as that." An LBL researcher said Papanek's suggestion for home testing in Los Angeles County appeared to be "an ill focused effort." "Recommending that everyone worry about radon is causing people who shouldn't be concerned about it to worry about it." "Most of the houses (with problems) are clustered…we need a focused effort finding places with high numbers." Radon experts immediately challenged the credibility of the county's radon study on the basis that it lacked consistency by mixing short- and long-term results from a wide range of sources. The October Times' article included results of the recently concluded EPA and DHS study involving a survey of 1,885 California homes (part of the EPA State Residential Radon Survey, SRRS). The SRRS study estimated 1% of Los Angeles County households had dangerous levels of radon and 0.6% for all of southern California households. For California overall, the SRRS study estimated that 2.4% of homes may have excessive radon levels, third from the bottom of radon levels among the 34 SRRS project states.

Although the SRRS survey involved many more homes than the Liu et al. (1990) study, it utilized short-term radon screening measurements. Consequently, its estimates and conclusions carried less weight with DHS officials and LBL researchers than the Liu et al. (1990) study. DHS continued to use 0.8% from the Liu et al. 1990 study as the statewide rate for homes with radon levels exceeding 4 pCi/L radon.

On February 4, 1991, the Santa Barbara News-Press ran an article titled "Radon may lurk in 2,000 homes, tests find" (Burns, 1991). The article reports the results of a radon survey of 80 Santa Barbara (city) area homes by Ed Keller, a University of California Santa Barbara geologist and professor of environmental studies. Keller found radon "hot-spots" within Santa Barbara and in surrounding areas. The high radon homes were associated with the Rincon shale, an organic rich mudstone with naturally elevated background uranium levels. Simultaneously, Don Carlisle, professor emeritus at the University of California Los Angeles Department of Earth and Space Sciences, was reaching conclusions similar to Keller. Carlisle also tested 80 homes and found 75% of measurements in one anomalous radon area exceeded 4 pCi/L. The highest measurement for a home in the county reported by Carlisle was 58.4 pCi/L, with other high measurements ranging from 25.9 pCi/L to 41.6 pCi/L. Keller and Carlisle urged all homes on or near the Rincon shale be tested for radon. Keller drew a radon "hazard area" around the shale and, using air photos, counted 7,100 buildings within it. He estimated that about 25%, or 1,800 buildings, would likely exceed 4 pCi/L.

DHS followed up on the University of California studies and its results were reported in an April 18, 1991 article by the Los Angeles Times titled: "High Levels of Radon Found in Residences : Health : Santa Barbara discovery is the first time widespread amounts of the radioactive gas have been detected in a California neighborhood" (Corwin, 1991). The article reports that the state Health Director said that isolated cases of high radon levels have been found in some neighborhoods in the state, but that this is the first time a "hot spot" has been found in California. More than half of the 140 homes tested by DHS in the Santa Barbara area exceeded EPA guidelines. Thirty showed radon levels five times higher than the guidelines. The article quoted Santa Barbara County Health Care Services deputy director as saying the people shouldn't panic. "They'd have to live in a house for decades and decades with very high levels for it to have the potential to do damage." She also said that Santa Barbara residents living in areas with high radon levels do not have higher rates of cancer, according to county Cancer Registry statistics. The DHS Director still recommended all residents in southern Santa Barbara County and northern Ventura County test their homes for radon. He is quoted as saying "some people feel the EPA has overreacted…but we're taking a conservative approach." "Instead of quibbling about it, we'd rather be safe and go with the EPA standards." While there is some disagreement about exposure levels, there is no dispute that radon can cause lung cancer.

Although not part of the Santa Barbara News-Press article, one should note that neither the Liu et al. (1990) study of 310 randomly selected homes nor the DHS statewide study of 1,885 randomly selected homes (SRRS) identified the high radon area at Santa Barbara. In 1993, Carlisle and a graduate student published a paper on their Santa Barbara and Ventura counties radon work in the scientific journal Indoor Air (Carlisle and Azzouz, 1993). In this paper, they criticize using random surveys for identifying anomalous radon areas. The authors state, "Simple random sampling aims ideally to avoid bias by making every house equally selectable and, as a consequence, obliterating differences among sub-populations which may, or may not exist within the whole." Consequently, sub-populations or measurements representing anomalous radon areas such as at Santa Barbara may not be recognized as such. Alternatively, Carlisle and Azzouz advocate exploring for abnormally radon–prone areas using a geological approach similar to that used for mineral deposit exploration. In the mineral industry, exploration based upon geological models of occurrence is far more likely to find anomalous occurrences than random sampling. The Santa Barbara-Rincon Shale hot spot was found by a deliberate geologic exploration approach, not by random surveys. Hobbs and Maeda (1996) also concluded that the Santa Barbara hot spot was not found in the Liu et al. (1990) survey because, "…random sampling is ill-suited for the evaluation of small subpopulations." The Carlisle and Azzouz, and Hobbs and Maeda statements about random survey shortcomings are consistent with the caution by Liu et al. (1990) quoted above. However, DHS continued to use a random survey approach for subsequent radon studies in the late 1990s.

EPA and LBL Radon Potential Maps and the California Radon Perspective

In 1993, the EPA released its Map of Radon Zones for the United States. This was the first radon potential map that covered the entire nation and an important step in raising radon awareness with the public, government and health organizations. Figure 3 shows the California portion of the EPA Map. The map shows radon potentials as zone classifications based on ranges of estimated average county indoor-radon levels. The average county indoor-radon ranges are: Zone 1, > 4 pCi/L; Zone 2, 2 to 4 pCi/L; and Zone 3, < 2 pCi/L. The EPA map shows Santa Barbara and Ventura counties as the only Zone 1 counties in California. Of the remaining 56 California counties, 29 are Zone 2 and 27 are Zone 3. The EPA radon potential map did not change the perspective that radon is not a significant problem in California, except for Santa Barbara and Ventura counties. Of interest is that the original draft of the California portion of the EPA map showed Santa Barbara and Ventura counties as Zone 2 counties. After it was pointed out that the draft map showed no indication of the state's only official radon "hot-spot" known at that time, the EPA decided to change Santa Barbara and Ventura counties to Zone 1 counties on the final map. A negative consequence of that change is that both counties are shown as Zone 1 counties in their entirety, even though the "hot-spot" area represents only slightly more than 2% of the combined two-county land area. Unfortunately, by using average indoor-radon levels to represent county radon potentials, the EPA map also reinforced the California perspective in unanticipated ways. First, many of those trying to use the map do not have a feel for the significance of different average indoor radon levels with regard to risk. A 1 pCi/L average compared to a 3 pCi/L average, or a 3 pCi/L average to a 4 pCi/L average doesn't imply much difference in risk to the average person because the numbers are close to each other and small. More problematic is that some individuals do not recognize the Zones are averages. They interpret the Zone definitions to mean that no homes in Zone 2 or Zone 3 counties exceeded 4 pCi/L, and all homes in Zone 1 counties exceed 4 pCi/L. The author recently found a statement online justifying not testing homes in an EPA Zone 3 California county because the Zone has "predicted indoor radon levels of less than 2 pCi/L" and that is less than the level EPA considers hazardous.

Several years after EPA released its map, LBL released two radon potential maps for the U.S. developed as part of their High Radon Project (LBNL, 2016a). Fewer people are aware of these maps than the EPA radon map. One High Radon Project map shows radon potential by estimated county geometric mean radon level. The other map shows county radon potentials by the estimated ratio of homes exceeding 4 pCi/L. Figure 4 shows the California portion of the High Radon Project > 4 pCi/L ratio map. The LBL High Radon Project used a Bayesian statistical approach to arrive at these estimates. LBL used the same short-term SRRS indoor-radon database as the EPA used for its map but modified the data mathematically to simulate yearlong measurements. High Radon Project researchers assumed a lognormal distribution for all county indoor-radon populations when calculating their estimates.

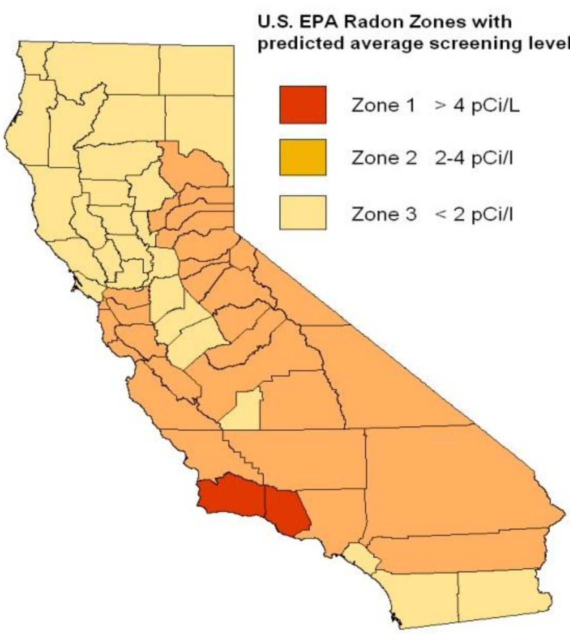

Figure (3): 1993 U.S. EPA Radon Zone classifications for California counties

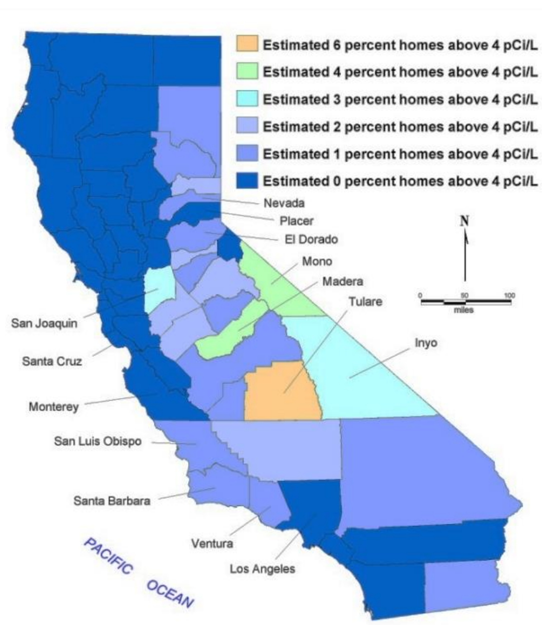

Figure (4): LBL High Radon Project > 4 pCi/L home ratios for California counties

(data from http://energy.lbl.gov/ie/high-radon/ctypred.htm, retrieved 2016-8-1))

The LBL High Radon Project maps show very low radon potentials for California counties, further reinforcing the prevailing California radon perspective (LBNL, 2016b). The > 4 pCi/L ratio map shows 33 California counties having an "estimated 0 percent homes above 4 pCi/L." The author has been unable to find High Radon Project documentation describing exactly what this statement means. It could be interpreted literally as meaning 0% of homes in a county were expected to exceed 4 pCi/L. It seems likely that much of the public may have interpreted it this way. Alternatively, the LBL researchers may have intended for this category to represent 0.5% or less of homes in a county were expected to exceed 4 pCi/L. If so, indicating this clearly on their map would have helped prevent any potential misinterpretations by map users. Homes have been measured exceeding 4 pCi/L in a number of these 33 counties. One of the High

Radon Project Map "zero" counties is Los Angeles. Results of the Liu et al. (1991b) study using yearlong radon measurements are strong evidence against a "zero" > 4 pCi/L home ratio for Los Angeles County. The results also show it is likely Los Angeles County's >4 pCi/L ratio exceeds 0.5%. The Liu et al. (1991b) study did not list population estimates for Zip Code areas in their study but U.S. Census Bureau 2010 population estimates are available for their Zip Code areas (U.S. Census Bureau, 2016a). Using these population estimates, over 365,000 people reside in the Liu et al. (1991b) high and moderate Zip Code areas in Los Angeles County (see Figure 5). Based on the Liu et al. (1991b) estimates of 14% and 8% > 4 pCi/L homes for their high and moderate potential Zip Codes and the 2010 census data, at least 38,900 individuals likely reside in homes with > 4 pCi/L in these Zip Code areas. This population estimate does not include the population for Zip Code 91301 (25,488), because it is partially in Ventura County. Another 454,000 people reside in Liu et al. (1991b) low potential Zip Code areas in Los Angeles County. Using their 1% estimate of > 4 pCi/L homes for low potential Zip Code areas, an additional 4,540 individuals would be residing in homes exceeding 4 pCi/L in these Zip Codes. While 43,440 persons in > 4 pCi/L residences is a small percentage of Los Angeles County's 9.8 million population, it is significantly more than most people would assume for a county with an "estimated 0 percent homes above 4 pCi/L.". Additionally, there are more people living in > 4 pCi/L homes in anomalous radon areas in other parts of southern Los Angeles County. Examples of such areas are the Palos Verdes area (Churchill, 2012b) and the moderate radon potential areas, shown on the CGS radon potential map for southern Los Angeles County (see Figure 6 and Churchill, 2005). The northern half of Los Angeles County may contain anomalous radon areas as well but a radon map has not been completed at this time. The Liu et al. (1991b) study area population only represents about 3.7% of the Los Angeles County population. The estimated 43,440 persons in >4 pCi/L homes in this area represents 0.44% of the county population. Given these percentages and the known existence of other anomalous radon areas, it is very likely that the county ratio of >4 pCi/L residences for all of Los Angeles County exceeds 0.5%.

Note the similarity between the high and moderate radon potential Zip Code areas in Figure 5, developed from yearlong home measurements, and the CGS high and moderate radon potential areas in Figure 6 developed using short-term radon screening tests grouped by geologic unit. While high and moderate zones from the two maps do not match exactly, they clearly point to the same southwestern portion of Los Angeles County as having anomalous radon potential. The Liu et al. (1991b) study did not cover other parts of the county. The single countywide radon potential designations used by the EPA and LBL maps provide no indication that such radon potential variability exists in Los Angeles County. Although yearlong radon tests are best for assessing annual radon exposures, the anomalous radon areas in California can be identified using a geologic approach and either short-term screening tests or yearlong tests. Ultimately, the Liu et al. (1991b) study results for Los Angeles County raise serious questions about the accuracy and usefulness of the High Radon Project map radon potential predictions for Los Angeles and other California counties.

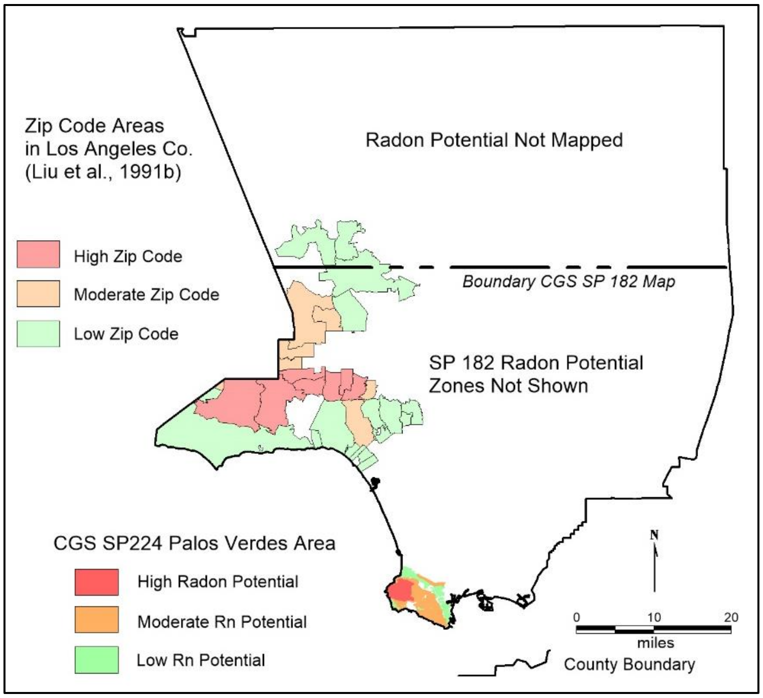

Figure (5): Liu et al. (1991b) high, moderate and low radon potential Zip Code areas in Los Angeles County, California

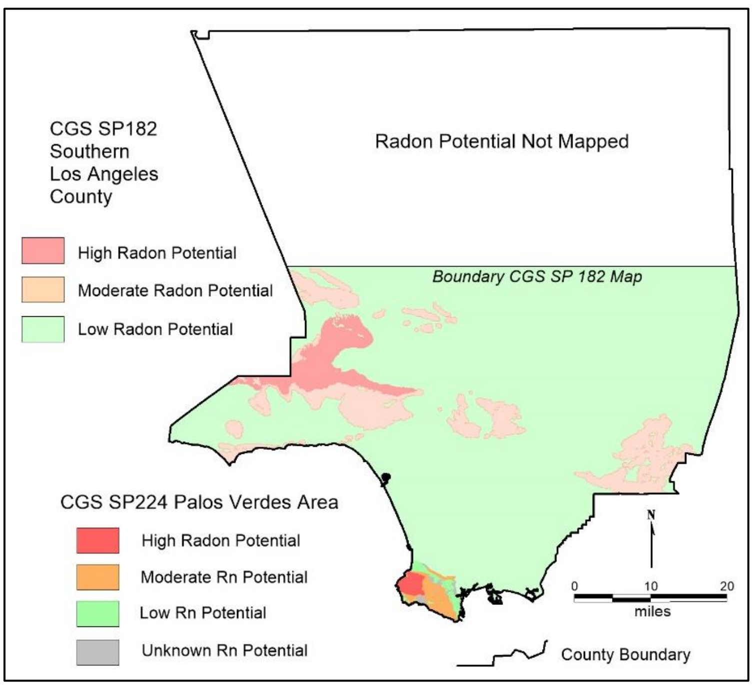

Figure (6): Southern Los Angeles County high, moderate, low and unknown radon potential areas (Churchill, 2005 and Churchill, 2012b). The different potential area colors relate to the different reports.

The limitations and shortcomings of both the EPA Radon Map and the High Radon Project > 4 pCi/L ratio map just discussed have significant consequences for California. Especially problematic is the inability of both maps to indicate the small but significant anomalous radon areas present in a number of California counties. Because of this inability, both maps have reinforced the perspective that radon is not a significant issue in California. Both the EPA and LBL radon maps are based on 1,885 randomly selected indoor radon-screening measurements for California. To put this number of measurements into perspective it is interesting to consider the radon potential map for England and Wales completed in 2007 by the Health Protection Agency (HPA) and the British Geological Survey (BGS). The combined land area and population for England and Wales are about 59,500 square miles (154,000 square kilometers) and 56.6 million people (ONS, 2016). The land area and population for California are about 156,000 square miles (404,000 square kilometers) and 39.1 million people (U.S. Census Bureau, 2016b). The HPA and BGS used approximately 460,000 long-term radon test results in developing the England and Wales radon potential map (Miles et al., 2007). EPA and the LBL High Radon Project used 1,885 short-term radon measurements in developing their radon potential maps. California probably does not need 460,000 radon measurements to identify and characterize its anomalous radon areas. However, the EPA and LBL High Radon Project radon potential maps' shortcomings and accuracy issues for California relate in part to their development from too few radon measurements.

Summary Comments on Historical Origins of California's Radon Perspective

By 1994, the perception that radon is not a significant problem in California, with the possible exception of the Santa Barbara area, was the established dominant perspective with the public, among many public health and government officials, and in the private sector (e.g., real estate agents). Information provided above shows three factors within California influenced this perspective. First, there were widespread media reports about radon survey results mostly finding few or no homes exceeding 4 pCi/L in California compared to other states. While the media reported the survey results correctly, these surveys were limited in their ability to identify anomalous radon areas. They missed the Santa Barbara-Rincon shale hot spot and radon anomalous areas later identified by CDPH-CGS radon surveys and mapping. Second, the media reports about radon regularly contained statements by DHS officials and LBL researchers that radon is not a significant problem in California as it is in other states, constantly reinforcing that perspective. Third, DHS and LBL strongly criticized EPA and other agencies that called for radon testing of every home in California or in a county. These public criticisms and debates between different groups of experts were likely confusing and possibly frustrated a public trying to understand what they should do regarding radon. As papers on risk communication point out (e.g., Hintenlang, 1995; and Johnson, 1995), such "debates" provide a reason for the public to believe that radon risks are being overstated and to put off any definitive action, such as home testing. The EPA Map of Radon Zones and the LBL High Radon Project maps provided ways for individuals to obtain basic information about radon risk at a location of interest quickly. However, the information the maps provide is very general. Given the state's geologic complexity, the average county radon level, or overall county ratio of > 4 pCi/L homes, may not be representative of any particular location of interest within a California county. It is incorrect to assume that no > 4 pCi/L homes occur in a High Radon Map "estimated zero percent homes above 4 pCi/L" California county. Based on CGS and other work, some of these counties likely have hundreds to thousands of > 4 pCi/L homes. Ultimately, the EPA Map of Radon Zones and the LBL High Radon Project maps reinforced the public perspective that California does not have a significant radon problem.

After 1995, interest in the indoor-radon issue declined in California and radon news items are much less common in media as illustrated in Figure 7. This may have been inevitable and only partially for the reasons just discussed. According to Hintenlang's review of public risk perception regarding radon (Hintenlang, 1995), the public considers 12 issues in developing its views on risk associated with environmental agents. Hintenlang found that not even one of the issues indicates radon is a high-risk problem and most permit the public to view radon as a low risk problem. Additionally, the risk of radon exposure does not seem real to a majority of the public because they do not know of a single person who has died from lung cancer due to radon exposure (Johnson, 1995).

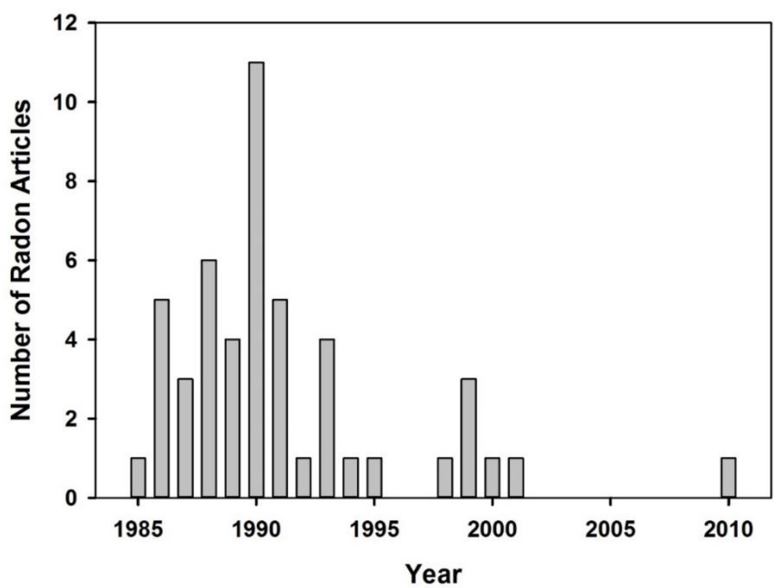

Figure (7): Radon articles in the online Los Angeles Times digital archives—1985 to 2010

The California radon perspective is correct in that, compared to states like Iowa, California is at the other end of the indoor-radon exposure spectrum. Unfortunately, continued downplaying of the radon issue in California and declining public interest over time seems to have changed the perception from "radon is not a significant problem in California" to "California does not have radon problems." The latter perception is not correct. Lost in that perspective are the Liu et al. (1990) cautions that the surveys like theirs employed in California could miss significant anomalous radon areas. That happened with the Santa Barbara-Rincon shale radon hot spot.

A more accurate perspective is that California does not have large radon problem areas like some states, but does have a number of small but significant anomalous radon areas. What makes these small anomalous radon areas significant is that hundreds to tens of thousands of individuals are likely exposed to > 4 pCi/L radon levels in residences in some of these anomalous areas.

CGS and CDPH Mapping and Survey Activities to Identify Anomalous Radon Areas in California

As mentioned in the introduction, CGS has completed 10 radon potential maps, and two more maps are nearing completion. Completed radon potential maps are available for eight coastal counties, the Lake Tahoe Area, and the Palos Verdes area (see Figure 1). CGS has identified one or more high radon potential areas in all but one of its completed radon study areas. It identified only moderate, low and unknown radon potential areas in Orange County. For CGS maps completed so far, high radon areas are typically small. High radon potential areas total from as little as 1.3% to almost 18% of county land areas for counties mapped so far. The estimated populations within high radon potential areas commonly range from about 4,000 to 40,000. An exception is the combined high radon areas in southern Los Angeles County, which may contain over 400,000 residents. Information from completed CGS maps suggests a high likelihood that future CDPH-CGS radon surveys and mapping will identify additional anomalous radon areas in California.

An important part of the CGS mapping approach is indoor-radon data from homes on individual geologic units known or suspected of having high radon potentials. The CDPH Radon Program obtains these data through indoor-radon surveys for areas prior to their mapping by CGS. Since 2004, CDPH has conducted indoor-radon surveys of all or parts of 20 counties. The surveys use address lists of homeowner occupied homes to solicit survey participation. CGS develops address lists using digital geologic maps and GIS software to try to ensure generation of sufficient data for suspected anomalous radon geologic units for their statistical characterization and comparison. After these geologic units are covered, the remaining goal is to obtain some data for as many other geologic units as possible in the survey areas.

Increasing Radon Awareness in California

Since 2003, the CGS and CDPH cooperative effort has provided new indoor-radon data and detailed radon potential maps that will, it is hoped, help reform the California radon perspective. Detailed information about the CGS maps is available in Churchill (2012a). Figure 8 shows the number of radon measurements per year in the CDPH radon database. Radon testing laboratories voluntarily provide these measurements to the CDPH Radon Program. Also shown are radon measurements for CDPH radon surveys each year. Note the increase in measurements per year starting about 2004 to 2006.

Two things likely influenced the increase in measurements shown in Figure 8 after 2003. First is the start of the CDPH-CGS radon surveys in 2004. The surveys increase radon awareness where they are conducted in several ways. A letter soliciting survey participation is sent to selected homeowner occupied addresses in survey areas. The letter also provides a little information about radon and how to obtain additional information. For surveys conducted this past winter, CDPH sent 26,262 solicitation letters to residents in Santa Clara County, 15,080 to Fresno County and 9,890 to Madera County. CDPH and county environmental health departments often do press releases at the beginning of surveys and post survey and radon information on their websites and social media sites, such as Facebook. These actions also increase public radon awareness. In December 2015, the Fresno Bee newspaper printed an article based on the CDPH press release about the 2015-2016 radon surveys in Santa Clara, Fresno and Madera Counties (Fresno Bee, 2015). The Fresno Bee daily circulation is over 150,000. Santa Clara County posted information about the 2015-2016 CDPH survey on its county website and on its county Facebook page. While Figure 8 shows CDPH surveys directly contributed to the increase in radon measurements per year, the increase is greater than survey measurements alone.

Secondly, increased web presence may have influenced the increase of radon measurements after 2003 as shown in Figure 8. About 2003 the CDPH Radon Program web site became more prominent and CGS added a radon webpage to its website (http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/radon). The CGS radon webpage initially contained general information about radon and links to the CDPH Radon website, EPA and other radon information websites. In 2005, CGS began posting PDF copies of its radon potential maps and accompanying reports for free viewing and downloading. Currently 10 radon maps and accompanying reports are available for viewing and downloading on the CGS radon webpage (see map examples Figures 9 and 10). Although data are not available for some years, Figure 11 shows a significant increase in CGS radon webpage utilization between 2004 and 2014. Internet searches using the key words radon and the county or study area name for a completed CGS radon potential map (e.g., radon San Mateo or radon Lake Tahoe) will typically have links to the related CGS maps and reports at or near the top of the query response list.

The CGS radon potential maps are at 1:100,000-scale (1 inch = 1.58 miles or 1 cm = 1 km), which allows individuals to find the location of their home or a point of interest and the radon potential for the immediate area. Some county websites have either links to reports and maps on the CGS radon webpage or have a version of the county's CGS radon map on their website. The CDPH Radon Program website has links to CGS radon maps and reports. CGS typically receives several requests each year for the digital map files of the radon potential layers for completed counties or study areas. These requests are usually from environmental consulting companies or disclosure companies, and CGS has provided copies of these digital files at no charge.

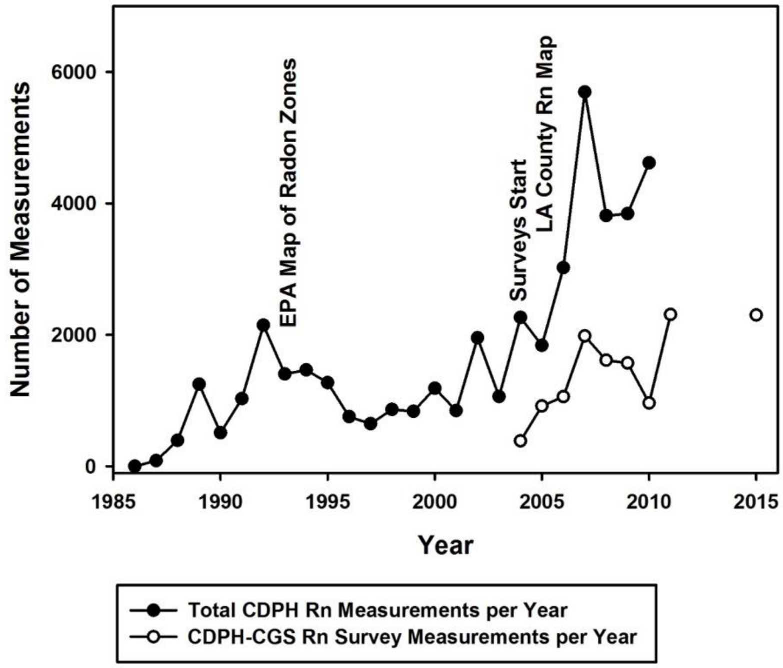

Figure (8): Radon measurements voluntarily provided to CDPH by radon testing laboratories and CDPH-CGS radon survey measurements by year

The CDPH-Radon Program has maintained an online radon Zip Code database for a number of years and it can be useful in parts of California where CGS has not completed a radon potential map. The database indicates those Zip Code areas that have many measurements and ones that have few or no measurements. It also indicates those Zip Code areas that have many measurements exceeding 4 pCi/L and ones that have few or no such measurements. While these Zip Code data are not suitable for detailed statistical analysis, they may prompt some to do radon testing or additional radon research in Zip Code areas with more measurements exceeding 4 pCi/L.

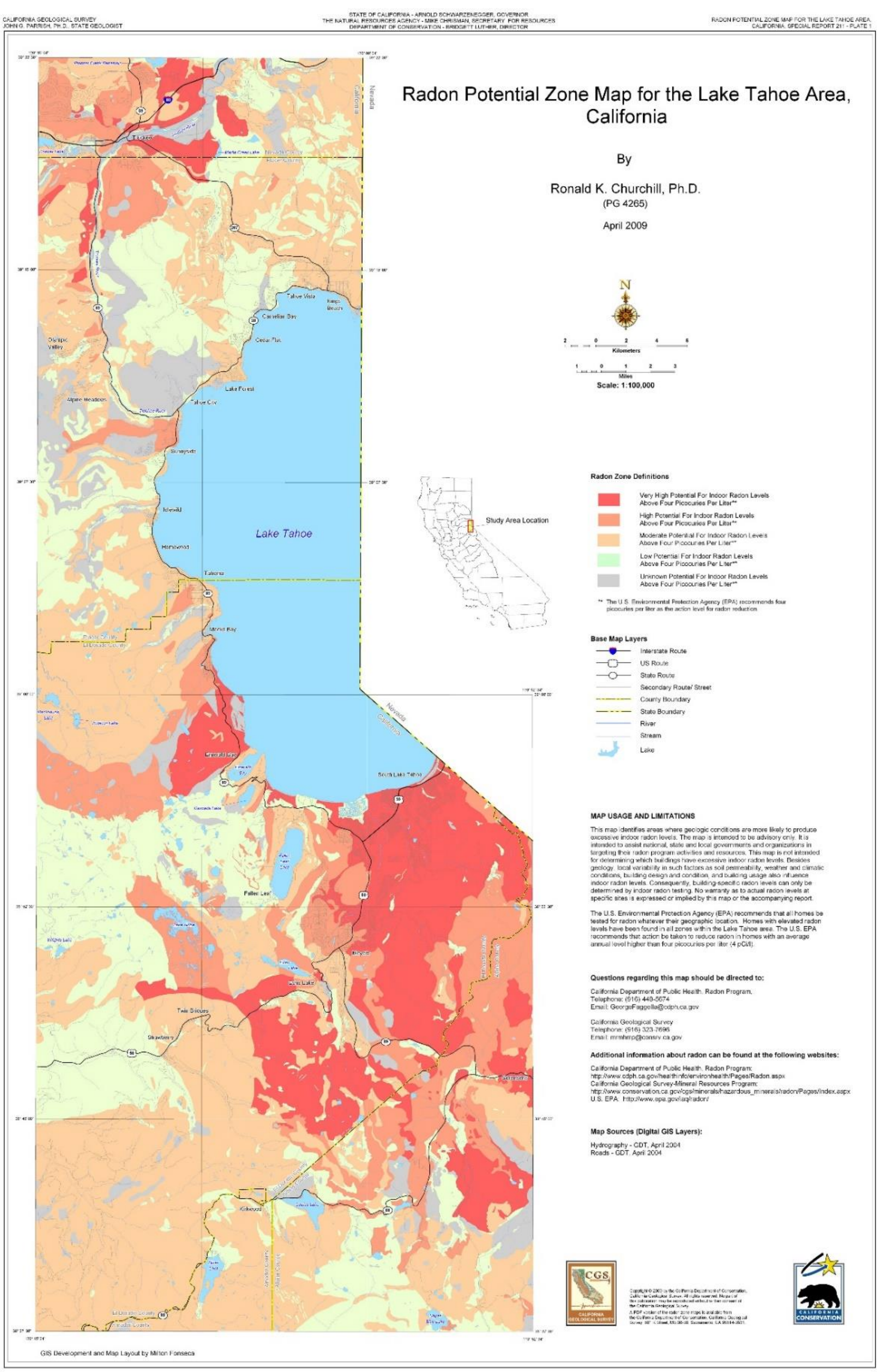

Figure (9): An example of a CGS radon potential map, shown here much reduced in size (Churchill, 2009).

Figure (10): A portion of the Orange County radon potential map showing the typical level of detail for CGS radon maps. Moderate radon potential is orange, low radon potential is green and unknown radon potential is gray (Churchill, 2015).

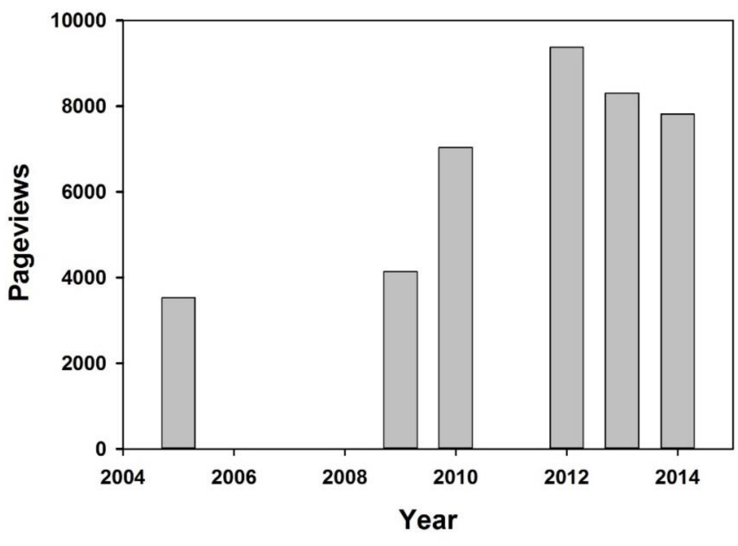

Figure (11): CGS radon website pageviews by year.

Most Californians do not know that a radon component in Phase 1 environmental reviews for California construction projects has become more common in recent years. CGS issued Note 48 in 2013 (CGS, 2013). This is a checklist of items and topics that consulting engineering geologists must address in their reports related to construction projects for California public schools, hospitals, and essential services buildings such as fire stations as required under California Code of Regulations (CCR), Title 24, California Building Code (CBC 2913). The permitting agency in California for public schools is the Division of the State Architect (DSA). Hospitals and skilled nursing facilities are under the jurisdiction of the Office of Statewide Health Planning and Development (OSHPD). CGS serves as an official advisor under contract with these two state agencies and uses Note 48 to review consultants' reports for completeness. Note 48 requires review of seismology and earthquake ground motion, liquefaction and seismic settlement, slope stability and other geologic hazards or adverse site conditions. Note 48 item 31-E lists "Radon-222 gas" as a review item, noting that it is not a statewide issue but may be pertinent to a particular site. If so, the consultant should communicate the relevant radon information to the building design team. During the last year, CGS staff engineering geologists reviewed 440 school projects and 30 hospital projects. Ten school projects in the last six months addressed the radon issue in their engineering geology and seismology reports (Jennifer Thornburg, CGS, oral communication). Of these ten projects, two used CGS radon potential maps in their review. One project site is located in a CGS mapped high radon potential area and the consultant recommended the architect/engineer for the project consider radon in the design of the proposed building improvements. The other project site is located in a CGS mapped low radon potential area and the consultant made no radon recommendation. For the remaining eight, seven project sites are not in areas with CGS radon maps. For these, consultants used the EPA radon map for radon information at six sites and one consultant referenced bedrock geology and CDPH radon Zip Code data for their site. One site has a CGS radon map showing low radon potential at the site, but the consultant instead referenced nearby CDPH 2010 radon testing (probably the 2010 CDPH radon Zip Code database) to conclude the site has low radon potential.

San Luis Obispo County updated its guidelines for engineering geology reports in October 2013 (Papurello, 2013). It added Item 25, "Radon and other hazardous gasses." The San Luis Obispo guidelines indicate that radon evaluation is only appropriate in the county where radon is an issue. The guidelines provide guidance on how to determine if radon is an issue at a particular location in the county. The guidelines also require review of the CGS SP 208, Radon potential in San Luis Obispo County, California, report and maps when addressing radon potential in engineering geology reports for sites in the county. The guidelines include the URL for SP 208. The guideline requirement for radon has recently led to radon being considered as an issue at sites for a new California Department of Forestry and Fire Protection (Cal Fire) firehouse, and at two school sites in San Luis Obispo County. Cal Fire has made a commitment for radon resistant new construction (RRNC) at the firehouse (Donald Lindsay, CGS, oral communication).

CGS Note 48 and the San Luis Obispo County guidelines for engineering geology reports are requiring engineering geology consultants to become more familiar with the radon issue and with available radon information resources, including CGS radon potential maps. Eventually, this knowledge may lead consultants to consider radon as an issue at sites other than schools, hospitals, skilled nursing facilities and essential services buildings.

As of July 14, 2016, an online interactive radon map became available on the CGS Radon webpage. The interactive radon map displays radon potential information for those counties and areas where CGS has completed a radon potential map. This interactive map makes it easy and quick to identify locations of interest and obtain radon potential information for these sites. It also facilitates accessing radon maps and report PDF files, and retrieving digital GIS radon potential layers and related GIS metadata for counties and areas with CGS radon maps. Locations of interest may be selected manually, using the cursor, or an address or location key words may be typed into the search box and the location will be identified on the map. Placing the cursor on the location symbol and clicking the left mouse button will cause a pop-up box to appear. In addition to radon information at the site, the pop-up box also contains links to the related CGS radon map, report and related GIS files.

The interactive radon map only provides information within areas of California with a completed CGS radon potential map. The areas colored dark red, red, orange, green or gray, representing very high, high, moderate, low and unknown radon potentials in Figure 12 are areas with completed CGS radon maps. Figure 13 is a screen view showing the location of a site obtained by entering a school name in the query box in the upper right of the screen; for this example, Palos Verdes High School was used. Figure 14 shows the pop-up box with radon information for the Palos Verdes High School site.

Although the proportion of California with completed CGS radon potential maps appears small in Figure 12 (also see Figure 1), over 15 million people reside in these areas. Using the interactive radon map, residents and other stakeholders interested in radon now can quickly and easily retrieve radon potential information, access related radon map and report PDF files, and download related digital GIS files for CGS radon potential maps for any location in California within a completed CGS radon map. As new radon potential maps are completed, CGS will add the radon potential areas from these maps to the interactive radon map.

Summary and Conclusions

The perspective that radon is not a significant problem in California developed in the 1980s and early 1990s. Several things within California contributed to this perspective. One was the media reports about a number of small random radon surveys finding few or no homes with > 4 pCi/L radon levels. A second contributor was the repeated statements by state health officials and LBL researchers that California does not have a significant radon problem like other states. Media reports of strong disagreements between California public health officials and LBL radon researchers on one side and county health officials and the EPA officials on the other side of the issue to test all homes for radon also likely influenced the perspective. They may have contributed to public apathy about radon in California. However, that apathy may have occurred

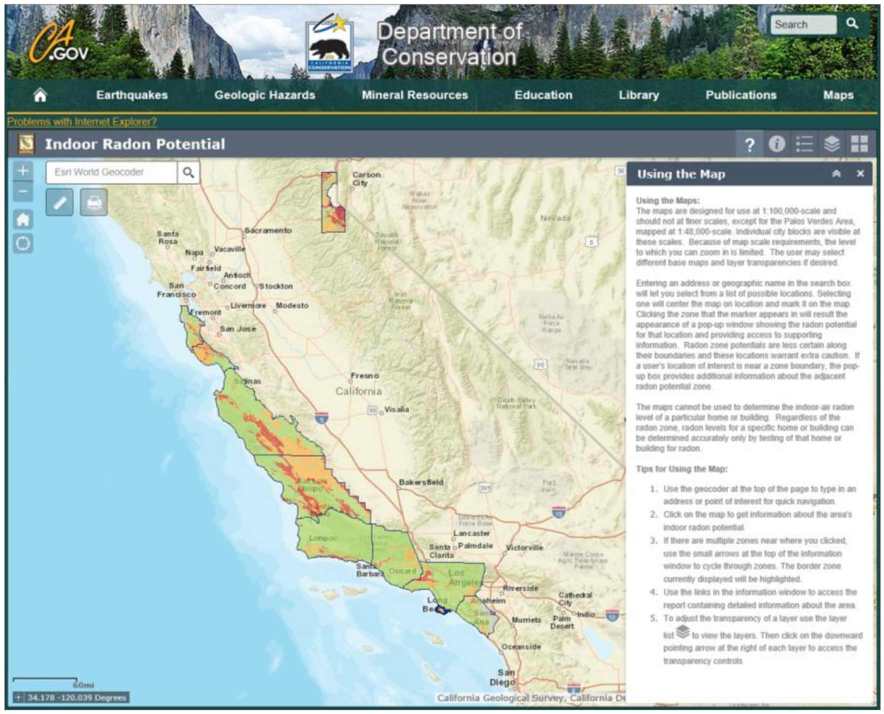

Figure (12): A screen view of the Department of Conservation, CGS interactive radon potential map. Radon potential information is available within any of the dark red, red, orange, green or gray colored areas.

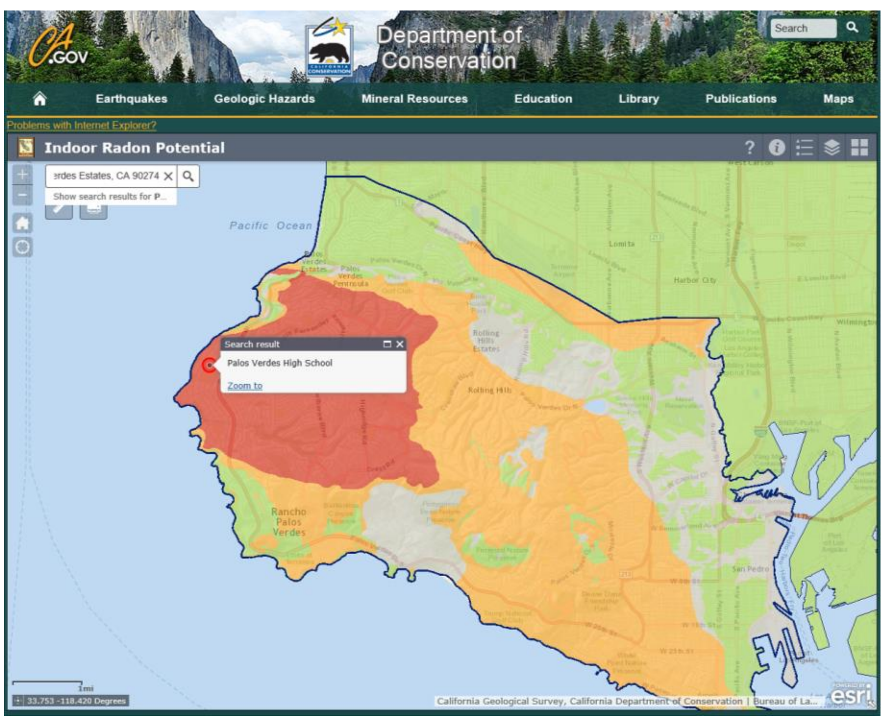

Figure (13): This computer screen view shows the location of a particular site of interest. In this example, "Palos Verdes High School" was entered in the search box in the upper right of the computer screen.

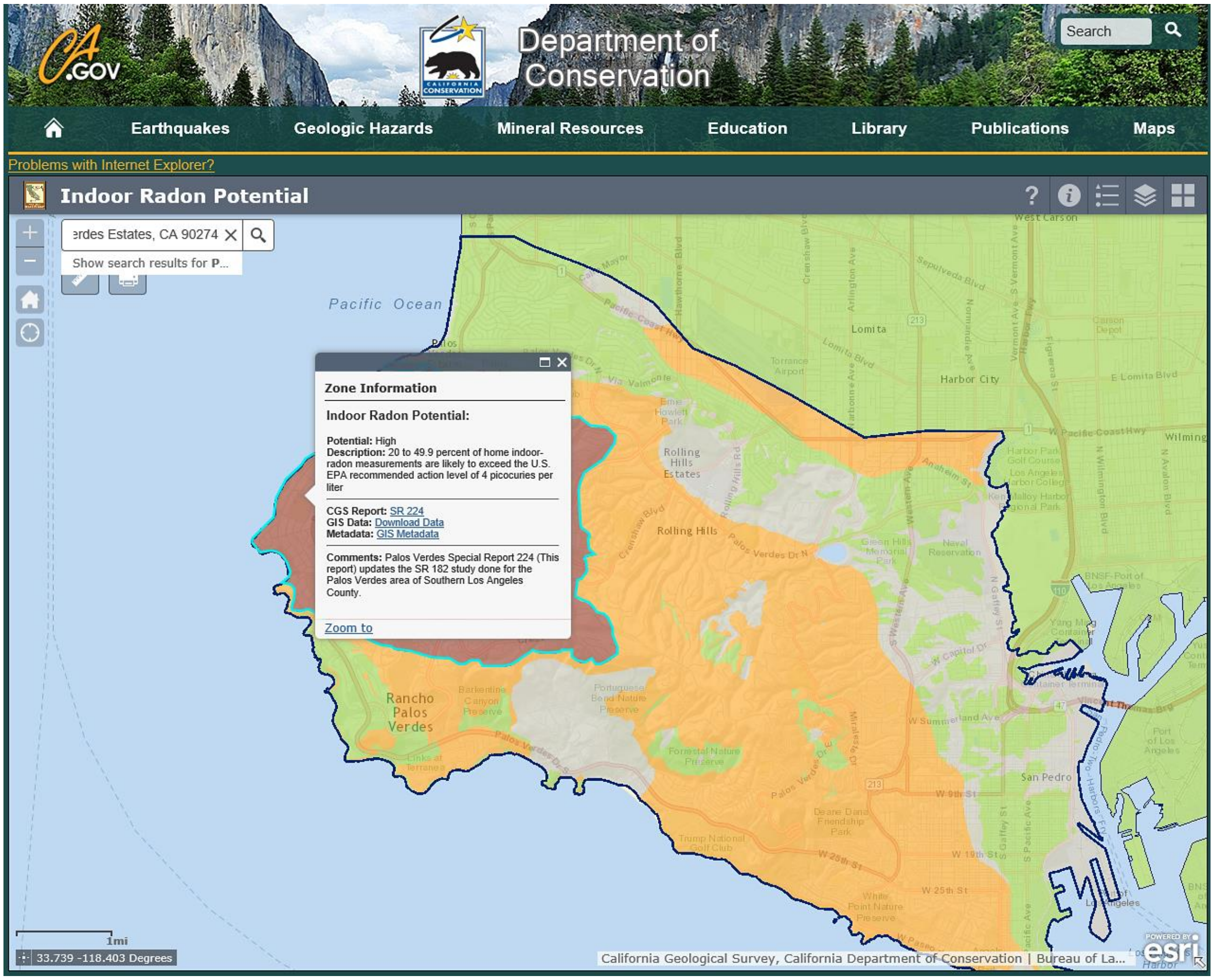

Figure (14): Computer screen view showing the interactive map pop-up box with radon information for the Palos Verdes High School location.[3]

anyway given the nature of radon risk and the inability of many persons to see that risk as personally significant. The EPA and the LBL High Radon Project maps further reinforced the California radon perspective by their inability to show the significant but sub-county sized anomalous radon areas that are typical in California. The focus of the joint effort by the CDPH Radon Program and CGS since 2003 is to document and publicize the presence of these anomalous radon areas in California. Focused radon surveys and development of detailed geologic based radon potential maps are accomplishing this. Interestingly, during the 1980s and 1990s DHS officials and LBL radon researchers repeatedly stated that elevated radon homes in California cluster in small areas. They repeatedly called for detailed radon studies to identify these clusters. Only one such study, Liu et al. (1991b) for eastern Ventura County and western Los Angeles County, was completed. Funding difficulties may have prevented other detailed

(3) In 2003, a student conducting a science fair research project discovered radon levels in some classrooms up to almost 50 pCi/L at Palos Verdes High School (Duval et.al., 2004; Fukumoto et al., 2003). Soon after this discovery, a radon remediation project successfully lowered classroom radon levels to near outdoor ambient radon levels.

studies during this period. The detailed radon studies that DHS and LBL called for are similar to what the CDPH Radon Program and CGS joint effort has been doing since 2003.

The new online CGS interactive radon map greatly simplifies obtaining radon potential information for any location in California within completed CGS radon potential map area. As the public, government agencies, consultants, real estate agents, and other stakeholders discover the interactive map, and consider the radon information they obtain, it is hoped a more accurate California radon perspective will emerge. That perspective is that radon is not as widespread a problem in California as it is in many other states, but California does have a number of relatively small anomalous radon areas. These areas may pose a significant health concern for those residing within their boundaries.

Knowledge gained from CDPH surveys and CGS mapping so far strongly suggests that additional anomalous radon areas remain to be discovered in California. Only after documentation of these areas can local residents, state and local public health officials and other stakeholders consider appropriate strategies and take steps to minimize their public health consequences.

Acknowledgements

The author would like to acknowledge the following individuals for providing information and helpful suggestions during the preparation of this paper: John Parrish, John Clinkenbeard, Fred Gius, Jennifer Thornburg, Donald Lindsey and Milton Fonseca (CGS); Nathaniel Roth (California Department of Conservation) and Natalia Deardorff (CDPH Radon Program). Thoughtful and thorough reviews by Michael Kitto and an anonymous reviewer greatly improved the quality of the manuscript.

References

Appleton, J.D., 2013. Radon in Air and Water; in Selinus, O. ed., Essentials of Medical Geology, Revised Edition. Springer, pp. 239-277.

Brookins, D.G., 1990. The Indoor Radon Problem. Columbia University Press, New York, 229 p.

Burns, M., 1991. Radon may lurk in 2,000 homes, tests find. Santa Barbara News-Press, February 4, 1991, article, pp. A1 and A4.

Carlisle, D., and Azzouz, H., 1993. Discovery of Radon Potential in the Rincon Shale, California – a Case History of Deliberate Exploration. Indoor Air, v. 3, pp. 131-142.

CGS, 2013. California Geological Survey – Note 48, October 2013, Checklist for the Review of Engineering Geology and Seismology Reports for California Public Schools, Hospitals, and Essential Services Buildings. Retrieved 2016-7-21: http://www.conservation.ca.gov/cgs/information/publications/cgs_notes/note_48/Documents/note_48.pdf.

Churchill, R.K., 2015. Radon Potential Zone Map for Orange County, California. Department of Conservation, California Geological Survey Special Report 232 map plate. Retrieved 2016-29-07: ftp://ftp.consrv.ca.gov/pub/dmg/pubs/sr/sr_232/SR232_Orange_RadonMap_Final.pdf.

Churchill, R.K., 2012a. A Geologic Mapping Approach to Identify Radon Hot-Spots in California and Ramifications for the State's Radon Risk Picture. American Association of Radon Scientists and Technologists, 2012 International Radon Symposium Proceedings, Las Vegas, 21 p. Retrieved 2016-7-29: http://aarst-nrpp.com/proceedings/2012/03_A_Geologic_Mapping_Approach_to_Identify_Radon_Hot-Spots_in_California.pdf.

Churchill, R.K., 2012b. Radon Potential in the Palos Verdes Area, California. Department of Conservation, California Geological Survey, Special Report 224, 64 p. Retrieved 2016-7-25: http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/radon/Documents/PV_Final_Report_05292012.pdf.

Churchill, R.K., 2009. Radon Potential Zone Map for the Lake Tahoe Area, California. Department of Conservation, California Geological Survey, Special Report 211, map plate. Retrieved 2016-29-07: http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/radon/Documents/SR_211_Map.pdf.

Churchill, R.K., 2005. Radon Potential in Southern Los Angeles County. Department of Conservation, California Geological Survey, Special Report 182, 52 p. Retrieved 2016-7-25 http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/radon/Documents/sr182text.pdf.

Corwin, M., 1991. High Level of Radon Found in Residences: Health: Santa Barbara discovery is the first time widespread amounts of the radioactive gas have been detected in a California neighborhood. Los Angeles Times, April 18, 1991 article. Retrieved 2016-5-23: http://articles.latimes.com/1991-04-18/news/mn-182_1_santa-barbara-county.

Duval, J.S., Fukumoto, L.E., Fukumoto, J.M., and Snyder, S.T., 2004. Geology and Indoor Radon in Schools of the Palos Verdes Peninsula Unified School District, Palos Verdes Peninsula, California. U.S. Geological Survey Open-File report 2004-1050. Retrieved 2016-7-25: http://pubs.usgs.gov/of/2004/1050/.

Feldman, P., 1990. Homeowners Urged to Test Dwellings for Radon Levels. Los Angeles Times, June 13, 1990 article. Retrieved 2016-5-23: http://articles.latimes.com/1990-06-13/local/me-243_1_radon-levels.

Fresno Bee, 2015. Free radon testing offered to residents in Santa Clara, Fresno and Madera counties. Fresno Bee December 14, 2015 edition. Retrieved 2016-7-25: http://www.fresnobee.com/news/local/article49805645.html.

Fukumoto, L.D., Duval, J.S., and Fukumoto, J.M., 2003. Classroom Radon Measurements in the Palos Verdes Peninsula Unified School District, Palos Verdes Estates, California. Proceedings of the 2003 International Radon Symposium—Volume 1, American Association of Radon Scientists and Technologists, Inc., pp. 3-18. Retrieved 2016-7-25: http://aarst-nrpp.com/proceedings/2003/2003_01_Classroom_Radon_Measurements_in_the_Palos_Verdes_Peninsula_Unified_Schoo_District_Palos_Ve.pdf.

Hintenlang, D.E., 1995. Risk Perception and Driving Forces for Indoor Radon Reduction Activities. 1995 International Radon Symposium 9 p. Retrieved 2016-7-25: http://aarst-nrpp.com/proceedings/1995/1995_09_Risk_Perception_and_Driving_Forces_For_Indoor_Radon.pdf.

Hobbs, W.E., and Maeda, L.Y., 1996. Method for Predicting the Occurrence of Small Radon Hot Spots from Randomly Chosen Data. 1996 International Radon Symposium, 8 p. Retrieved 2016-7-1: http://aarst-nrpp.com/proceedings/1996/1996_02_Method_for_Predicting_the_Occurrence_of_Small_Radon.pdf.

Johnson, R.H., Jr., 1995. Why Scientists and the Public Do Not Believe in Radon Risks. 1995 International Radon Symposium, 12 p. Retrieved 2016-07-20: http://aarst-nrpp.com/proceedings/1995/1995_07_Why_Scientists_and_the_Public_Do_Not_Believe_in_Radon.pdf.

Kizer, K.W., 1989. Is household radon contamination a problem in California?. California Physician, pp. 35-37.

Kizer, K. W., Hayward, S.B. and Liu, K., 1990. Radon in California Homes. The Western Journal of Medicine, October 1990, Letter to the Editor, v.153, no. 4, pp. 446-447.

LA Times, 1990. Statewide Radon Testing Planned. United Press International article in the Los Angeles Times, January 6, 1990. Retrieved 2016-5-23: http://articles.latimes.com/1990-01-06/news/mn-501_1_statewide-survey.

LA Times, 1991. Unsafe Radon Levels Found in 14% of Homes. Los Angeles Times, October 16, 1991 article. Retrieved 2016-5-23: http://articles.latimes.com/1991-10-16/local/me-458_1_unsafe-radon-levels-found.

LBNL, 2016a. Lawrence Berkley National Laboratory High Radon Project, Old Home Page. Retrieved 2016-8-1: http://energy.lbl.gov/IEP/high-radon/oldhome.htm

LBNL, 2016b. High Radon Project, Predicted parameters of radon distributions within counties in the 48 conterminous states. Retrieved 2016-8-1: http://energy.lbl.gov/IEP/high-radon/ctypred.htm

Lichtblau, E. and Stammer, L.B., 1990. Studies Conflict Over Radon Danger: Health: Local officials cite survey in urging testing. But EPA, state authorities find problem less pervasive. Los Angeles Times, October 12 article. Retrieved 2012-3-7: http://articles.latimes.com/1990-10-12/local/me-2128_1_county-health-department.

Liu, Kai-Shen, Hayward, S.B., Girman, J.R., Moed, B.A., and Huang, Fan-Yen, 1990. Survey of residential indoor and outdoor radon concentrations in California. California Indoor Air Quality Program, Air & Industrial Hygiene Laboratory, California Department of Health Services, Berkeley, California 94704, prepared for: Laboratory Services Section, California Air Resources Board, Sacramento, California 95814, 128 p. The Executive Summary is accessible on-line. Retrieved 2016-5-23: http://www.arb.ca.gov/research/apr/past/a6-194-53_exsum.pdf.

Liu, Kai-Shen, Hayward, S.B., Girman, J.R., Moed, B.A., and Huang, Fan-Yen, 1991a. Annual Average Radon Concentrations in California Residences. Journal Air Waste Management Association, v. 41, no. 9, pp. 1207-1212.

Liu, Kai-Shen, Chang, Yu-Lin, Hayward, S.B., and Huang, Fan-Yen, 1991b. Survey of Residential Radon Levels in Ventura County and Northwestern Los Angeles County, Final Report September 1991. Indoor Air Quality Program, Air and Industrial Hygiene Laboratory, California Department of Health Services, 2151 Berkeley Way, Berkeley, CA 94704, 43 p.

Miles, J.C.H., Appleton, J.D., Rees, D.M., Green, B.R.M., Adlam, L.A.M., and Meyers, A.H., 2007. Indicative Atlas of Radon in England and Wales, HPA-RPD-033. Health Protection Agency and British Geological Survey, Health Protection Agency, Chilton, Didcot, Oxfordshire OX11 0Rq, UK, 29 p. Retrieved 2016-07-27: http://www.ukradon.org/cms/assets/gfx/content/resource_2686cs3a0844cee4.pdf.

Monmonier, M., 1997. Cartographies of Danger, Mapping Hazards in America. The University of Chicago Press, Chicago, Illinois 60637, pp. 173-186.

ONS, 2016. The Countries of the UK. Office for National Statistics-The National Archives, United Kingdom. Retrieved 2016-07-27: http://webarchive.nationalarchives.gov.uk/20160105160709/http://www.ons.gov.uk/ons/guide-method/geography/beginner-s-guide/administrative/the-countries-of-the-uk/index.html.

Papurello, B.E., 2013. San Luis Obispo County Guidelines for Engineering Geology Reports, Revised October 2013. San Luis Obispo County Planning and Building Department, 19 p. Retrieved 2016-07-26: http://www.slocounty.ca.gov/Assets/PL/pdfs/SLO+Geology+Guidlines.pdf

Santa Cruz Sentinel, 1988. State health director says radon tests premature. Santa Cruz Sentinel, September 14, 1988 issue, page A-7. Retrieved 2016-5-23: https://www.newspapers.com/newspage/68027227/

Stammer, L.B., 1988a. Test Homes for Radon, EPA Says: 7-State Survey Finds Radioactive Gas More Prevalent Than Believed. The Los Angeles Times, September 13, 1988. Retrieved 2016-5-23: http://articles.latimes.com/keyword/radon-gas/featured/4.

Stammer, L.B., 1988b. Radon Danger Found Minimal in Southland: Carcinogenic Gas May Exceed EPA Limit in Only About 1.2% of Area's Households. The Los Angeles Times, October 2, 1988 article. Retrieved 2016-5-23: http://articles.latimes.com/1988-10-02/news/mn-5144_1_radon-level.

Stammer, L.B., 1990. Levels of Radon Low in Homes in California: Health: A statewide sampling indicates that 1 percent of houses may harbor dangerous amounts of the radioactive gas. The Los Angeles Times, March 29, 1990 article. Retrieved 2016-01-27: http://articles.latimes.com/1990-03-29/news/mn-204_1_radon-level.

U.S. Census Bureau, 2016a. Zip Code population data generated using American FactFinder. Retrieved 2016-07-17: http://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml.

U.S. Census Bureau, 2016b. California Quick Facts, population and state land area data. Retrieved 2016-07-28: http://www.census.gov/quickfacts/.

U.S. EPA, 1993. EPA Map of Radon Zones. Retrieved 2016-07-25: https://www.epa.gov/sites/production/files/2015-07/documents/zonemapcolor.pdf