1995_36

AN INVESTIGATION OF FACTORS AFFECTING THE ENTRY OF RADON INTO STRUCTURES ON THE ISLAND OF GUAM*

Douglas L. Kladder
Colorado Vintage Companies, Inc.
Colorado Springs, CO

James F. Burkhart
Physics Department, University of CO at Colorado Springs
Colorado Springs, CO

Mark S. Thorburn
Western Regional Radon Training Center
Fort Collins, CO

Peter Q. Cruz
Radon Program, Guam Environmental Protection Agency
Harmon Plaza, Guam

ABSTRACT

Factors affecting the entry of radon-222 gas into structures on the Island of Guam were investigated during the summer of 1993. Research findings indicated that radon transport into buildings on Guam, and perhaps in other tropical areas, is driven by sub-grade soil pressure (positive with respect to atmospheric pressure) rather than interior buildings vacuums. Immediate and substantive increases in indoor radon concentrations were associated with environmental effects of wind and rain. Radon entry, and hence indoor radon concentrations, is significantly greater during the rainy season as opposed to the dry season. In the absence of mechanically induced interior vacuums in buildings, external environmental forces creating sub-slab pressures are the predominant factor in affecting radon entry in Guam.

Indoor radon potentials can be correlated to the locations where the underlying geology is limestone. Furthermore, the radon source appears to be within the first few feet of the surface of these limestones rather than uniformly distributed throughout the limestone.

The effects of seismic activity on radon entry are short-lived unless significant damage occurs to a structure. Radon entry during calm weather conditions may also be a function of the rising and falling of ocean tides.

---

* Permission granted by Elsevier Science to re-print this paper from The Science of the Total Environment, Special Issue on the Natural Radiation Environment, presented at the NRE VI International Symposium, June 5-9, 1995, Montreal, Canada, to be published in 1996.

INTRODUCTION

During 1991, the authors conducted a radon survey of schools on Guam, as directed by Guam Public Law 20-184. This study utilized short-term testing methodologies to determine the radon potential of schools on Guam. This study (Burkhart 1993) concluded that radon potentials were high in locations where buildings were constructed over surficial geologies of limestone, and quite low when constructed over volcanic geologies. This earlier study also speculated that the radon entry mechanisms on Guam were primarily due to sub-structure pressures caused by environmental effects, rather than negative building pressures caused by thermal stack effects as is the typical entry mechanism observed in colder climates.

The purpose of this current study, authorized by the Guam EPA, was to conduct radon potential studies in Public Buildings (other than schools) owned by the Government of Guam; to further investigate radon entry mechanisms on Guam, and to recommend methods for constructing radon resistant buildings on the island. These studies are similar to those previously performed on Guam schools in 1991. The work summarized in this paper was conducted during the summer of 1993 through January 1994. The full report may be obtained through the Guam Environmental Protection Agency (Kladder 1993/4)

Guam is an unincorporated territory of the United States. It is the southernmost island in the Marianas Archipelago, and located at 13 degrees 28 minutes north latitude and 144 degrees 44 minutes east longitude (approximately 3,700 miles west-southwest of Hawaii) (Tracey 1964).

The Island of Guam is 30 miles long and between 5 and 8.5 miles wide. It was formed through uplift, pyroclastic events and undersea lava flow along with subsequent coral building. The island is surrounded by coral reefs near the shore. The northern and southern halves of the island represent two distinct surficial geological areas of approximately equal size. The northern half of the island is a high limestone plateau rising up to 850 feet above sea level. The southern region is mountainous, of volcanic origin, with elevations from 700 to 1300 feet.

Guam's tropical climate is warm year round. Temperatures range between 75 and 86 degrees Fahrenheit, with a mean annual temperature of 81 degrees. May and June are the hottest months. The average yearly rainfall is approximately 90 inches. Constant tradewinds blow predominantly from the northeast during the dry season of December through April when drought like conditions can occur.

CORRELATIONS OF RADON POTENTIAL TO GEOLOGY

It was determined during the earlier school survey conducted in 1991, that a strong correlation existed between the highest radon concentration observed in a particular school and the geology underlying the school To further confirm this correlation, in 1993 we performed short-term measurements in public buildings owned by the Government of Guam. This survey tested 1,252 rooms within 161 buildings using open faced carbon canisters under short-term testing methods, in accordance with US EPA protocols for testing schools. The carbon canisters were analyzed by the Radon Measurements Laboratory at Guam EPA, utilizing Sodium Iodide crystal based detection equipment. Quality Control measures taken during this survey indicated an average coefficient of variation for duplicates greater than 4.0 pCi/L to be 3.34% with a maximum of 4.01%, average of reported blanks was 0.065 pCi/L, with none in excess of 1.0 pCi/L.

Assuming that the highest reading within a particular building was an indication of the localized radon potential, a comparison was made between the highest radon reading obtained in this survey for each building and the underlying geology, as determined from US Geological Survey Maps. These new data have been combined with the data obtained from the earlier 1991 school survey in Figure 1.

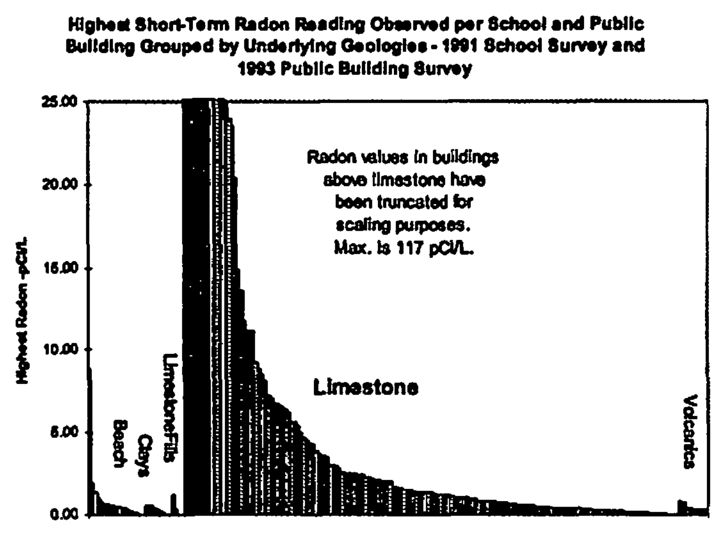
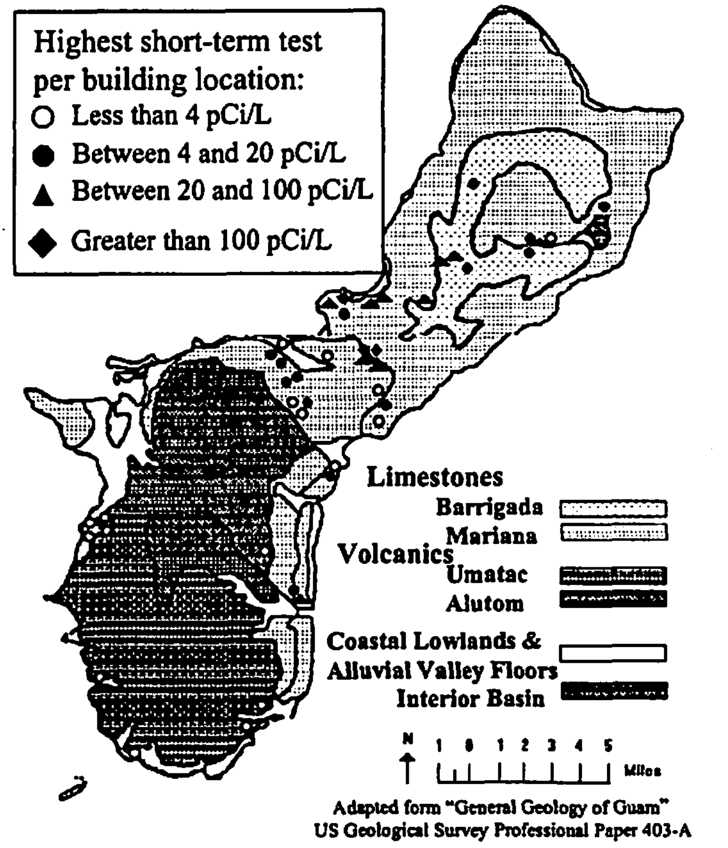


Figure 1- Correlation to Geology

Radon Potential in Buildings vs. General Geology



Adapted form "General Geology of Guam"
US Geological Survey Professional Paper 403-A

Figure 2

Based upon these data, a clear correlation exists between radon potential and geology. An anova test for variance gives a calculated F value of 5.22 (with a critical F of 3.88), indicating that the buildings above limestone surficial geologies come from a different statistical population than buildings above other geologies, with a 98% probability. The only anomalies observed were where alluvial deposits of limestone onto volcanic and beach zones. A suggested radon potential map, based upon geology, was made for Guam EPA and is depicted in Figure 2:

SURFICIAL GEOLOGY BASED BUILDING INVESTIGATIONS

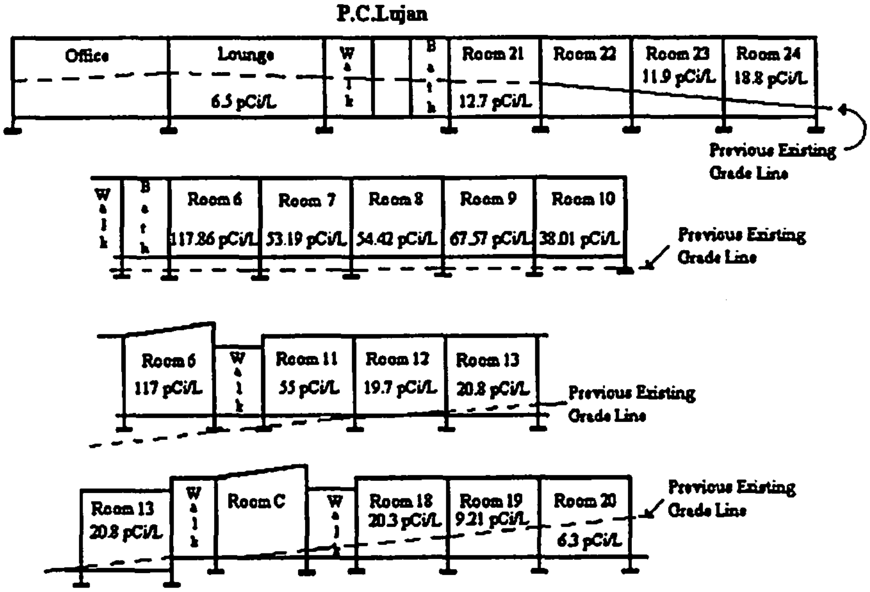
As was theorized by Burkhart and Kladder (Burkhart 1993, as well as Otten (Otten 1993), radium containing soils may be confined to surficial geologies, as a result of wind-borne deposition of uranium and radium bearing dusts. As reported earlier (Burkhart 1993), samples taken in a limestone quarry indicated radium-226 content at the surface of the quarry to be approximately 7 pCi/gram with samples taken below 4 feet to be at 1.0 pCi/gram or less. This would suggest the possibility that buildings constructed on undisturbed limestones could exhibit elevated indoor radon levels. Conversely, buildings constructed on limestones where significant cutting and filling of the site took place (removing the upper few feet of native limestones) would exhibit lower than expected radon concentrations. This hypothesis cannot be fully proven due to the lack of reliable construction drawings on the majority of the buildings investigated. The following results, however, would tend to support the hypothesis that the radon source is found within a few feet of the surface.

Case 1: Port Authority Buildings on Cabras Island.

Cabras Island is essentially a peninsula that was made from the importation of quarried limestone. A strict correlation to limestone, regardless of its source, would suggest that even buildings constructed on imported fills of quarried limestone would exhibit elevated levels of radon. However, out of 42 locations tested on this island the maximum reading was 1.23 pCi/L with a mean of 0.29 pCi/L. Since limestone fill was quarried many feet (up to 75 feet) below the native surface level, the radon source was, presumably, isolated to the limestone closer to the surface of the quarry and therefore not utilized in the construction of Cabras Island.

Case 2: PC Lujan Elementary School

Cut and fill drawings of the site for this elementary school were obtained and correlated to room radon concentrations. This information, illustrated in Figure 3, clearly points out the relation between radon concentrations and underlying native limestone versus imported or relocated fills. That is, where surface limestone was removed, low radon levels were detected and conversely where the building was constructed near to or on top of undisturbed native limestones radon readings were elevated. This adds credence to the theory that radon sources are associated with near-grade limestone surfaces.



Elevation Sketches Showing Previous Existing Grade Lines and Short-Term Radon Measurements from Aug. 1991

Figure 3 - Radon readings versus cut and fill of soil

Case 3: Guam Community College Facility at John F Kennedy High School:

This small building contains four individual classrooms. Based upon repetitive measurements, two classrooms on one end of the building exhibited quite elevated levels of radon, while the two on the other end did not. This was true even though all four rooms were constructed identically and had identical individual window style air conditioners. The radon measurements and the cut and fill patterns are shown in Figure 4. This building study further substantiates the correlation between native limestone surfaces and radon levels; and further suggests that some depth of imported fill impedes radon transport.

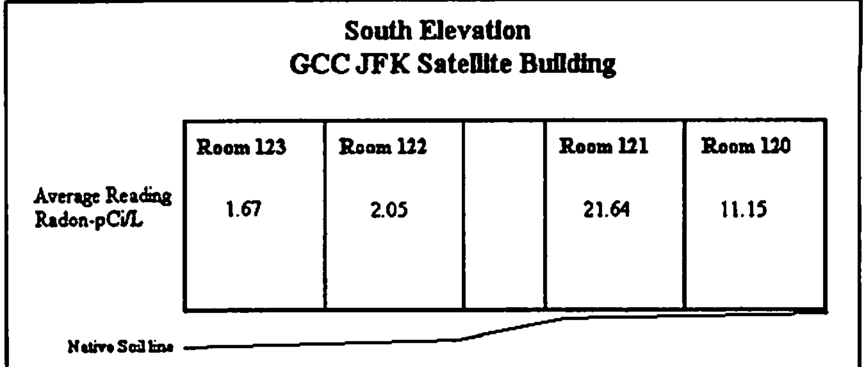


Figure 4 - Radon readings versus cut and fill of soil

MECHANISMS OF RADON ENTRY ON GUAM

Three buildings were selected from this survey for a more in-depth investigation of radon entry mechanisms on Guam. The methodology of these analyses was to install real time monitoring of the following variables with the following data collection devices:

	Variables	Equipment
Weather	Rain, wind speed, wind direction, barometric pressure, and outdoor temperatures.	Taylor WS-1000 Weatherstation
Building Pressure Dynamics	Sub-slab to building interior pressure differentials and Interior to exterior shell pressure differentials	Infiltec Model DM-20 modified for digital output and Cole Parmer T-40 differential pressure transmitters
Interior radon concentrations	Hourly variations in radon concentrations	Femto-Tech 410 and 510 continuous radon monitors (pulsed ion chambers)

Real time pressure and weather data were recorded at 20 second intervals by means of digital data collection devices connected to computers located on site. Radon information was collected on an hourly basis and manually entered into the data base.

Case 1: Guam Community College Annex at John F Kennedy High School

This building, consisted of a series of four classrooms. It is a one story reinforced concrete structure. All portions of the building were constructed at the same time with similar techniques. All rooms had louvers for ventilation and light, and all rooms had window style air conditioners. There were no hallways in this structure, which means that all rooms had at least two exterior walls and the two end rooms had three exterior walls. Consistent sequential short-term radon measurements indicated significantly different radon readings from one end of the building to the other (Figure 5).

GCC JFK Satellite

Radon-pCi/L	Room 123	Room 122		Room 121	Room 120
1st Reading	1.53	1.81		28.0	17.51
2nd Reading	1.81	2.28		15.28	4.79
Average Reading	1.67	2.05		21.64	11.15

Figure 5

Simultaneous, continuous radon readings taken in rooms 121 and 123 that exhibited very low and very high short-term radon readings show that although the amplitude of the indoor radon measurements were different, the changes in radon concentrations were very consistent. This would indicate that the distribution of indoor radon between the two ends of the building was due to the radon source rather than driving force differences. In fact, continuous monitoring of sub-slab to interior building pressure measurements confirmed similar slab pressure differentials in each end of the building (range -.14 to +.14 inches of water column), thus leading to the conclusion that radon source differences caused the indoor radon level difference between the two ends of the building (see discussion of surficial geology). The weather station was set up in room 121 (room exhibiting highest radon) with the data shown in Figure 6.

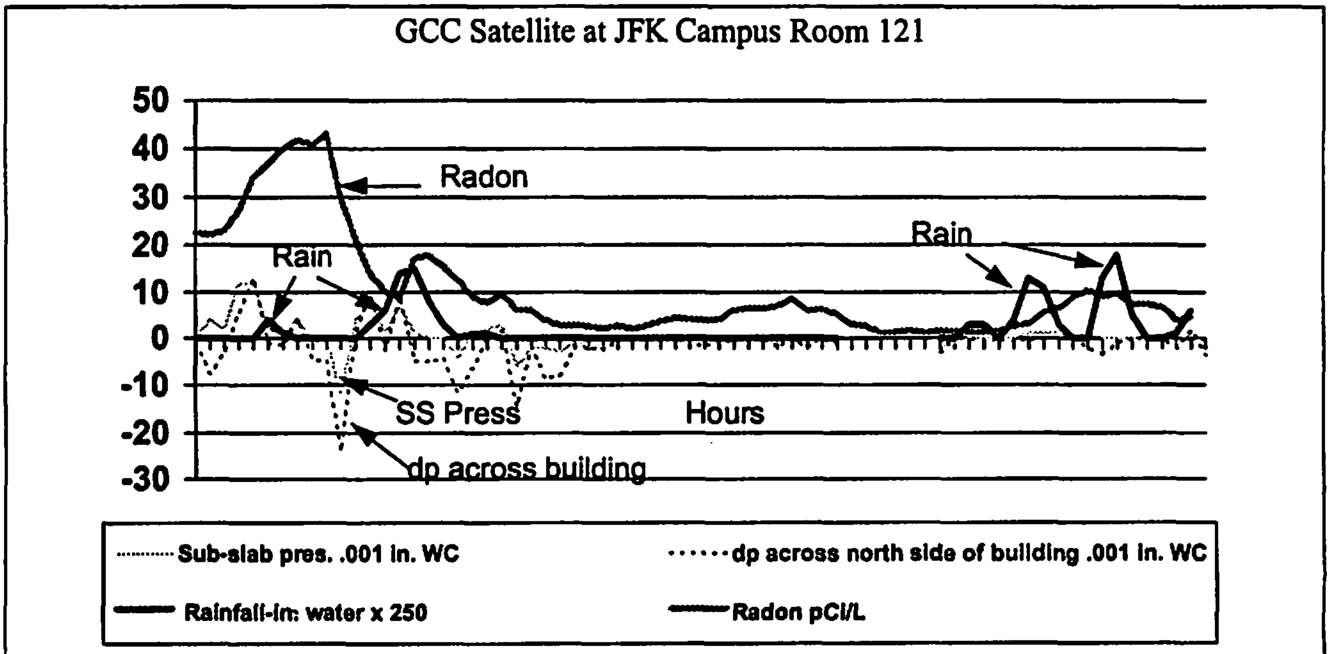


Figure 6

It should be noted that the data in Figure 6 is real time data and that radon readings have not been corrected for ramp-up time, which is believed to cause a 1-2 hour delay before the readings reflect changes in radon levels.

Figure 6 illustrates the correlation between sub-slab pressures and indoor radon concentrations, during the early portion of the study. Figure 6 also illustrates that the sub-slab to building interior pressure differentials tracked with the building interior to exterior pressure differentials, thus indicating good communication from the sub-slab fill to the outside gradeline. Dramatic spikes in radon concentration were observed shortly after rain showers throughout the measurement period. Also, changes in sub-slab pressures were observed to correlate very closely with wind speeds and directional changes. The good communication between the sub-slab and exterior grade would account for the pronounced impact of rain and wind observed in this building.

Case 2: Guam EPA Administration Building

This building was a large, single story, reinforced concrete, slab-on-grade office building. It consisted of a rectangular wing with a common hallway running down the center with offices on either side. The continuous monitoring equipment was set up near the exterior of the building on the northeast side. Figure 7 depicts the effect of wind direction on sub-slab pressures (driving force).

GEPA Building (north side) sub-slab pressures and building pressure differentials as a function of wind direction at speeds of less than 3 mph.

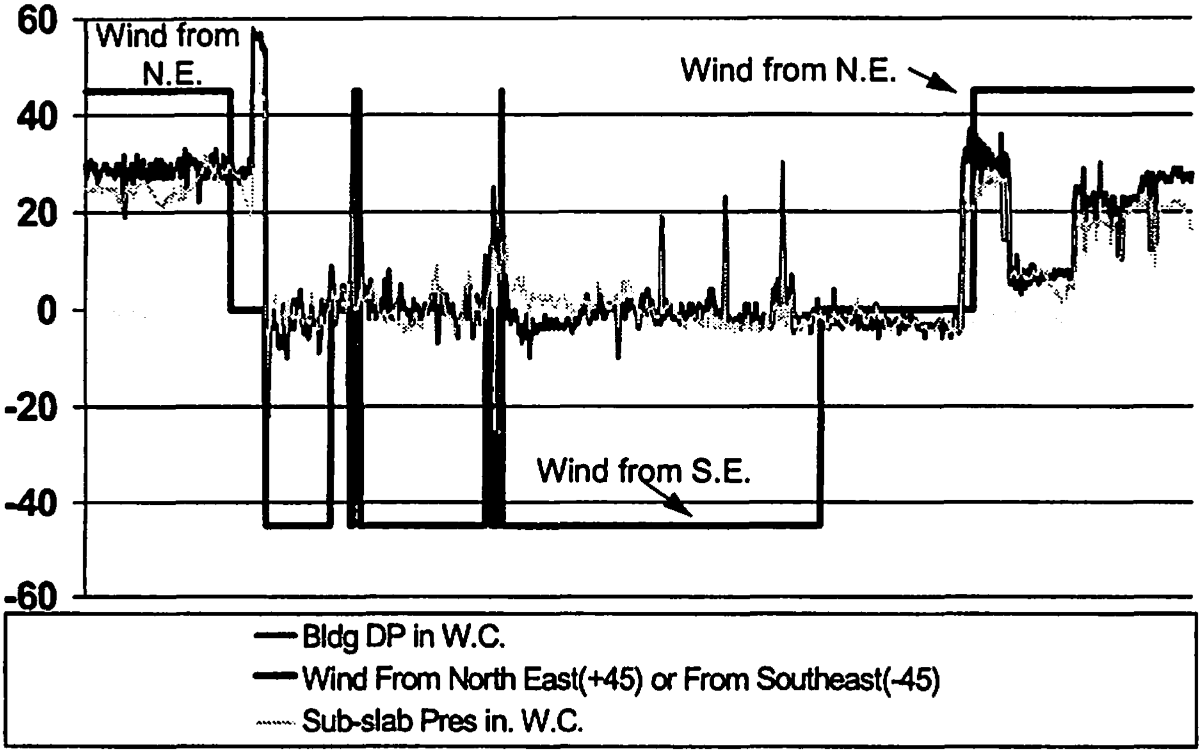


Figure 7

The data in Figure 7 strongly support the supposition that wind can exert pressure beneath the slab and lead to increased soil gas entry. Furthermore, Figure 7 also shows that the sub-slab to interior pressure differentials and interior to exterior building shell pressure differentials follow each other in both trend and magnitude. This, as in case #1, would indicate good communication from the sub-grade to soil outside the foundation, thus adding additional confirmation of the large impact that wind and rain has on soil gas and radon entry.

Case 3: PC Lujan Elementary School-Room 6

The data collection station was set up in this school (P.C. Lujan) shortly after an active soil depressurization radon mitigation system was installed in Classroom 6. This classroom was one room within a five classroom wing. The wing was also a single story, reinforced concrete structure with exterior hallways running along either side. Two walls of this particular classroom are exterior walls. There was no air conditioning in any rooms in this wing. Cross ventilation was accomplished by opening louvered windows located on the exterior walls. The short-term readings taken prior to the installation of the mitigation system in classroom 6 room are illustrated in Figure 8.

P.C. Lujan - Northwest Wing

Initial Short-Term Radon Measurements - August 1991 (pCi/L)

Plan View

	Room 6	Room 7	Room 8	Room 9	Room 10
	117.6	53.19	54.42	67.57	38.01

Figure 8

Prior to initiating data collection the radon mitigation system was disabled and the discharge sealed. Sub-slab to interior measurements were made via a connection to the ASD piping system, which was connected to a 3 feet deep pit beneath the slab near an intermediate footing which provided excellent communication to the sub-grade area. A portion of the readings occurred while school was in session which meant that the teacher opened the louvers during the school day for ventilation and light and closed them at night. The position of these windows (louvers) was recorded by the teacher and noted along with the data in Figure 9.

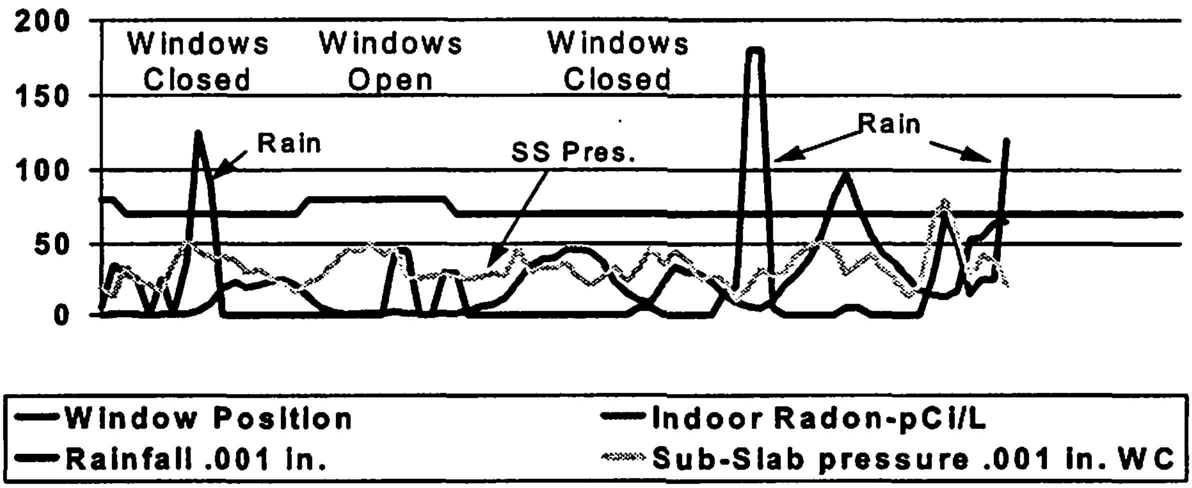


Figure 9

The data in Figure 9 shows that very large sub-slab to interior building pressure differentials were observed, independent of the position of the louvers. This is particularly noteworthy since the louvers make up over 30 % of the wall space on two sides of the classroom and, when open, would allow the interior of the room to equalize to atmospheric pressure, thereby negating any interior building induced negative pressures. The fact that sub-slab pressure differentials are positive when the louvers are wide open, confirms pressure driven entry from beneath the building, rather than negative pressures generated from within the building.

One can also see in Figure 9 the effect of significant rainfall on sub-slab pressures and subsequent radon levels, when the windows were closed and no significant ventilation existed.

Based upon this data it would appear that radon enters these tropical based structures via soil pressure caused by environmental effects such as rain and wind, rather than negative pressures in the buildings caused by temperature induced stack effects as seen in colder climates. This is a logical conclusion since temperature induced stack effects are caused by exterior temperatures that are colder than interior temperatures-a condition that does not exist in tropical climates such as in Guam.

EFFECT OF RAINY VERSUS DRY SEASON ON RADON ENTRY

To test the hypothesis that rain and its accompanying wind had a significant impact on radon entry, it was decided to re-test a statistically significant number of classrooms during the dry season (January) and compare the dry season results to tests conducted in the same rooms during the rainy season (August). Schools were selected to insure adequate representations of different surficial geologies and to insure that schools which exhibited high as well as low short-term readings during the previous rainy season survey were included. Once a school had been selected all classrooms within the school were tested.

Seasonal Comparison of Two Test Periods:

	Wet Season Testing	**Dry Season Testing**
Test Periods	August 7-31, 1991	January 7-10, 1994
Average daily rainfall for test periods as reported by Naval Air Station, on Guam	0.67 inches/day	0.01 inches/day

The short-term tests were conducted utilizing the same open face canisters and primary laboratory as used for the rainy season testing. Normal Quality Assurance and Quality Control measures were in place with the statistics shown below:

Number of school buildings	14
Number of rooms tested	291
Blanks (18)	100 % < 0.1 pCi/L
Duplicates	Average COV = 3.4% Highest COV = 4.75%
Spike 1 (from NAREL)	COV=6.89%
Spike 2 (from NAREL)	COV=2.53

Wet season versus dry season test results were compared for each school utilizing a paired, two-sample Student-t-test for means. The results are summarized in the table below along with a comparison to the underlying geology of the school.

School	Wet Season Average pCi/L	Dry Season Average pCi/L	Percent Change from Wet Season to Dry Season	Statistical Difference Between Seasons? (t/t_C)	Geology Class
P.C.Lujan	30.71	7.61	-75%	Yes (5.02 / 1.70)	LM
Harmon Loop	16.38	7.51	-54%	Yes (3.25 / 1.71)	LM
Wettengel	15.57	5.04	-68%	Yes (3.85 / 1.69)	LB
Finnegayan	4.66	2.11	-55%	Yes (7.82 / 1.78)	LB
Untalan Middle	4.38	1.58	-64%	Yes (3.75 / 1.68)	LM
Cathedral Grade School	2.17	1.77	-19%	*	B
Agana Heights	1.82	1.39	-24%	*	LM
Inarajan	0.18	0.07	-62%	*	VU
Merizo	0.16	0.07	-56%	*	VU
Harry S. Truman	0.14	0.17	27%	*	VA
F.Q.Sanchez	0.13	0.06	-53%	*	C
		Average % Change:	-46%		

Notes to table:

* Although the trend for schools noted by an asterisk is for lower radon readings to be observed during the dry season the differences between the rainy and wet season measurements for these particular schools are all less than the typical error seen with charcoal canister measurements.

Abbreviation	Geology Type	Radon Potential
LB	Limestone-Barrigada	High
LM	Limestone-Mariana	High
B	Beach Deposits	Low to Moderate
C	Clay	Low
VU	Volcanic-Umatac Formation	Low
VA	Volcanic-Aluton Formation	Low

The results of these tests clearly show the effect that rain and accompanying wind has on increasing radon concentrations in buildings on Guam. The information in the table above also points out that the effect of weather on radon entry rates is far more pronounced when the building is setting on limestone geologies with elevated radon sources. As also suggested by Schumann (Schumann 1992), we found a definite correlation between radon entry and rain (although our correlation was to indoor radon as opposed to soil gas measurements), but unlike Schumann we were able to observe a definite correlation of with wind. The source is still the controlling correlating variable, but weather is a major driving force for radon entry. The net effect of the differences in radon entry during the wet season as opposed to the dry season would be that the use of dry season testing alone would significantly under-predict the actual radon concentrations in buildings located in natural limestone geologies. Multiple measurements encompassing both seasons (or preferably, year-long measurements) would be more representative.

OTHER POTENTIAL ENTRY MECHANISMS

Tidal Effects

Given the evidence that radon entry can be caused by pressures beneath the building, it is reasonable to consider the effects that tidal changes can have on radon levels, especially when the base rocks are permeable limestone. Rising tides could cause a pneumatic pumping of soil gases up through fissures and soil pores. This is a difficult correlation to observe given the large effects of rain and wind that would mask this particular phenomenon. However, in one case where continuous monitors were left in two buildings during a very calm and dry period, the data suggests a 12 hour cycle as opposed to the typical diurnal cycle seen in other climates. Figure 10 shows this measurement along with tide levels.

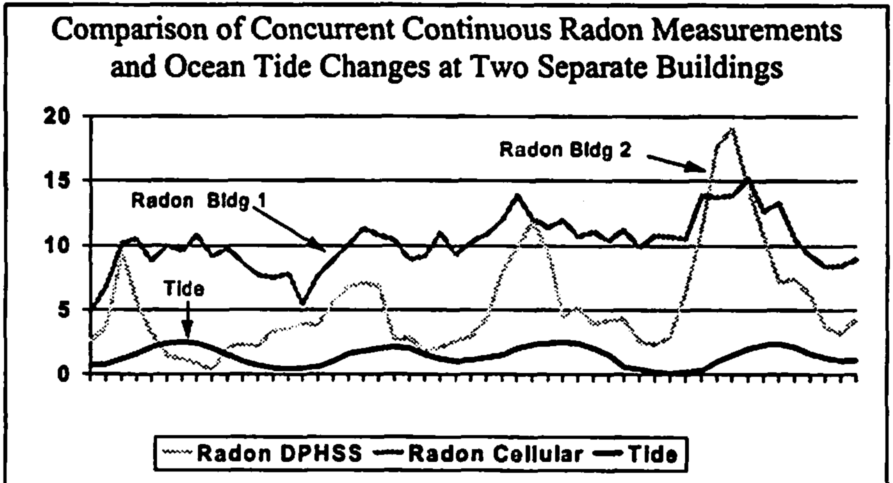


Figure 10

Effects of Earthquakes

The authors had the dubious good fortune of conducting this work during an 8.2 Richter scale earthquake. A continuous radon monitor was placed in the room described earlier as Case 3 which had not shown short-term radon measurements above 4.0 pCi/L. The measurement device was accumulating data prior to, during and after the occurrence of the earthquake and subsequent after shocks. (Note that the device was battery powered and unaffected by power fluctuations. The results of this testing are shown in Figure 11.

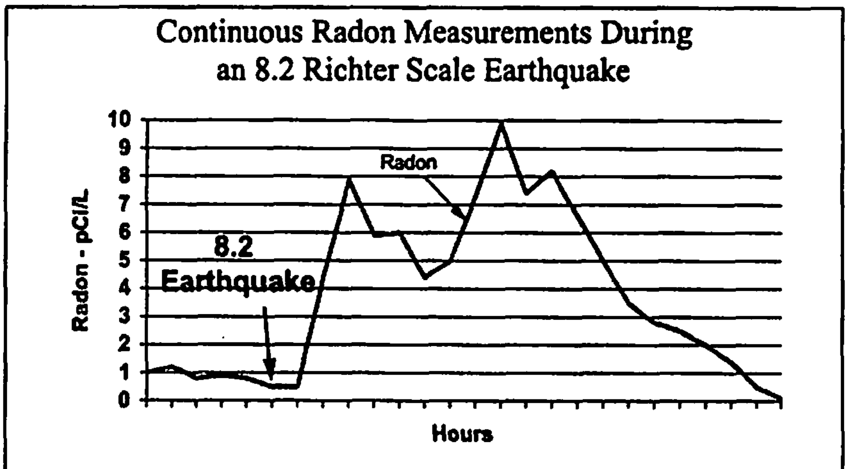


Figure 11

Figure 11 demonstrates radon peaks that can be associated with the earthquake and subsequent after shocks. It is interesting to note that the significant radon peaks were seen in a room that previously had shown very low levels of radon, thus suggesting that deep fissures and building cracks were momentarily opened up to allow radon transport, or this significant disturbance allowed soil gasses to be released from pore areas and "pulsed" to the surface. Furthermore, it can be noted that after the tremors stopped, the room readings essentially returned to their pre-earthquake readings (this was confirmed with follow-up short-term measurements).

As another part of this study, all public buildings that exhibited one or more rooms in excess of 4.0 pCi/L were retested as per normal protocols. The initial tests were performed prior to the earthquake and follow-up tests were performed after the earthquake, although all tests were done under identical climactic conditions. The net changes in each of the buildings re-tested are shown in Figure 12.

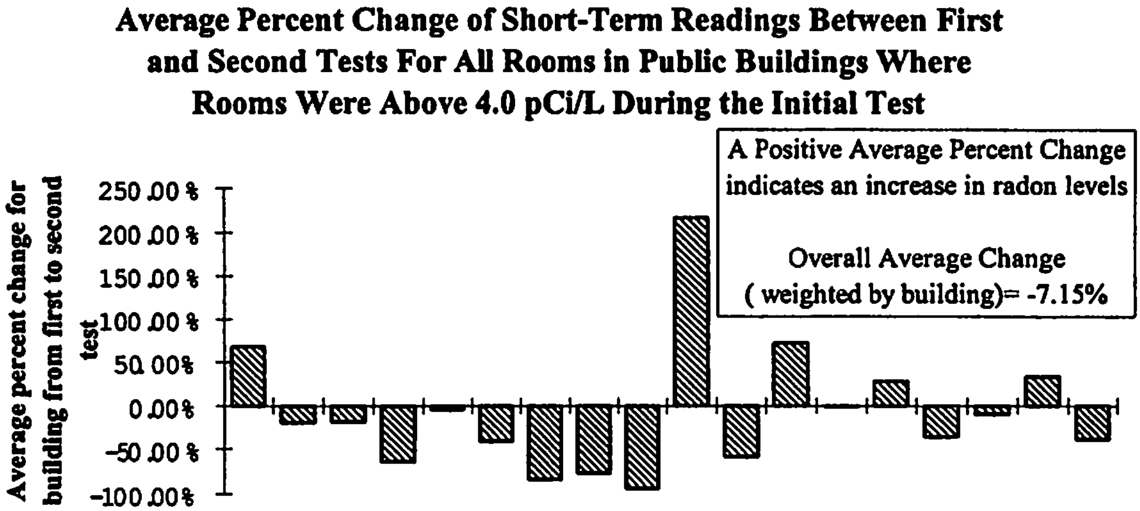


Figure 12

In the cases where radon levels significantly increased after the earthquake, visible structural damage occurred during the quake.

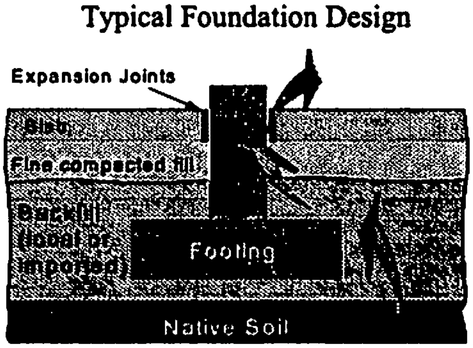


Figure 13

It should be noted that no buildings in this survey collapsed due to the earthquake. This is due to the type of construction on Guam that is designed to resist seismic events. One interesting construction detail common to Guam is the use of highly compacted crushed and wetted limestone beneath the slab of at least 18 inches in depth. In addition to structural strength this highly compacted fill provides a good barrier to radon entry. On the other hand, 2 inch gaps are deliberately left between the slab and the walls to allow independent movement of slabs and foundation walls during earthquakes. See Figure 13. This gap, along with the gap along the footing, allows for radon entry during normal times and an enlarged pathway during earthquakes (as well as after) if the wall movement is severe. However, it is not the authors' recommendation to remove this design feature, but rather to identify it as a significant radon entry pathway.

SUMMARY AND IMPLICATIONS

This study further validates earlier findings that a strong correlation exists between indoor radon levels in Guam and the presence of native limestone surficial geologies. It would appear that the predominant source is in the upper few feet of the limestone.

Rain and wind are the major driving forces for introducing radon into buildings sitting on top of limestone deposits in Guam. Pressure driven convective flow is the predominant entry mechanism in Guam.

Short-term radon readings can be on the range of 46% lower during the dry season as compared to the rainy season. Either rainy season readings or preferably multiple season readings should be used to avoid false negatives.

Tides may cause a pumping action that increases radon entry, but it would appear to be a very small effect compared to weather related influences.

Earthquake effects are short-term, except where major structural damage occurs, and then only in areas of high radon potential.

Entry into buildings is largely around perimeter edges and not through the center of the slab due to construction techniques of using deep and well-compacted limestone.

REFERENCES

Tracey, Joshua I., et.al., General geology of Guam. Geological Survey Paper 403-A, U.S. Government Printing Office, Washington D.C. 1964.

Burkhart, J.F., Kladder, D.L., Castro, F., Radon Distribution on the Island of Guam and Correlations to Surficial Geology and Deposition Models, International Radon Conference Proceedings, 1993.

Kladder, D.L., Burkhart, J.F., Thorburn, M.S., Guam Public Building Survey, Vol. I-III, Colorado Vintage Companies, Guam Environmental Protection Agency, 1993-4.

Kladder, D.L., Burkhart, J.F., Radon Survey In Schools and Residential Structures, Guam, USA, Vol. I-II, Colorado Vintage Companies, Guam Environmental Protection Agency, 1991.

Otton, James K., Asher-Bolinder, S., Elevated Indoor Radon Associated With Soils Developed on Pleistocene Limestones In Tropical and Subtropical Climates, International Radon Conference Proceedings, 1993.

Schumann, R.R., Owen, D.E., Asher-Bolinder, F., Effects of Weather & Soil Characteristics on Temporal Variation in Soil-Gas Radon Concentrations, Geological Society of America, Special Paper 271, 1992.