Enclosure 1: Project description of the project entitled

RADON GAS MIGRATION THROUGH SOIL AND INTO INDOOR ENVIRONMENTS

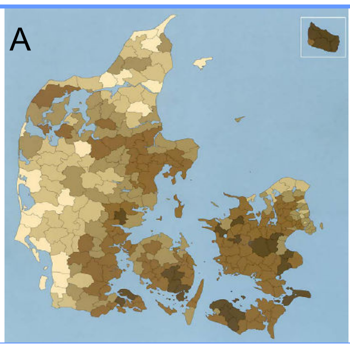
Summary Emission of radon from the subsurface is the main source of radon gas accumulation in residential buildings. This research proposal addresses the relation between vapor transport mechanisms in soil underlying building foundations and entry of radon to indoor environments. The objective is to obtain a thorough understanding of the underlying controls and provide a theoretical framework allowing for improved radon risk evaluations and technical solutions to prevent and reduce radon intrusion to buildings.

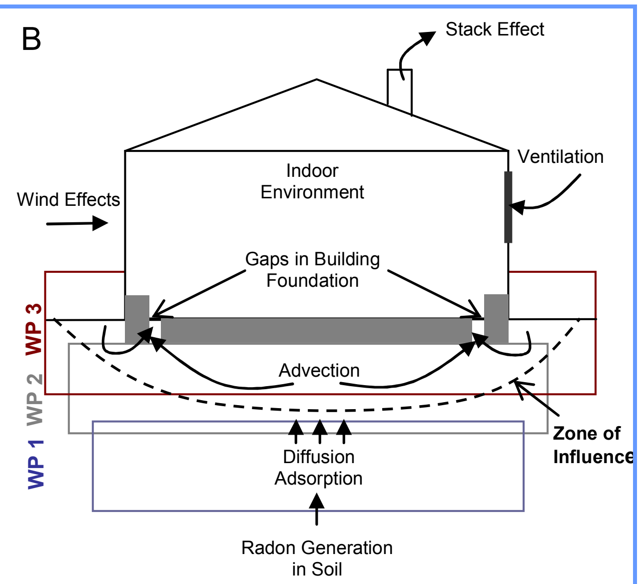
Background

Radon arises naturally in the subsurface from the radioactive decay of radium. Radon gas enters buildings from the underlying soil and through gaps and cracks in the foundation [1]. This is a worldwide health concern since long-term inhalation of radon has been shown to be the second leading cause of lung cancer after smoking. Reports indicate that radon is responsible for about 2% of all deaths from cancer in Europe [2]. In Denmark 14 % of all dwellings have elevated radon concentrations resulting in approximately 250 radon-related deaths every year (Fig. A) [3, 4]. In spite of that, the focus on and use of constructional precautions (e.g., installation of a membrane or ventilation system) to avoid radon intrusion is limited in Denmark compared to other Nordic countries [3, 5].

The processes in soil controlling the final entry of radon to indoor environments take place in the *zone of influence,* defined as the soil within which vapor transport is governed by a lower air pressure inside the building (Fig. B). The complex transport mechanisms occurring in this soil zone are not fully understood and represent a knowledge gap when evaluating radon entry to buildings.

A. Map of Denmark illustrating areas with high risk of elevated radon concentrations in indoor air (dark regions on the map) [3].





B. Conceptual model of processes affecting the risk of radon intrusion on site-scale. In the *zone of influence* transport is governed by the building underpressurization (advection). In deeper soils, transport is dominated by concentration gradients (diffusion). Adsorption of radon onto soil grains takes place across the soil profile depending on the organic matter content of the soil. Work packages (WP 1-3) are described in the following chapters.

Objectives and perspectives

The goal of this research project is to provide the theoretical framework needed to predict radon gas migration through the zone of influence and into buildings. Expected results will allow for improved risk assessment and prevention of potential radon intrusion to indoor environments. The below table summarizes the main objectives and perspectives.

Objectives	Perspectives
○ To achieve a validated conceptual model of radon intrusion to buildings including the relative significance of various factors influencing size of the *zone of influence*. ○ To calibrate novel analytic risk models for prediction of radon migration towards building foundations.	○ To provide an approach for site-specific risk assessment of buildings located in areas with high radon concentrations in the subsurface. ○ To improve chances of indentifying residential buildings with hazardous radon concentrations.

Experiences and results obtained from this project will be of great applied importance for authorities and consultants dealing with radon and pollutant risk management of developed and undeveloped land [6]. In addition, the project is likely to result in increased focus and additional research on radon migration at Aalborg University and its partners: Rambøll and Århus University.

State-of-the-art: Radon migration through the zone of influence

The fraction of radon gas (^{222}Rn and ^{220}Rn) released from the soil particles accumulates in the soil gas phase and spreads through unsaturated pores and fractures. The transport is driven by differences in concentration (diffusion) [7] and in total pressure (advection) [8, 9]. During transport, radon attenuates by radioactive decay (^{222}Rn half life is 3.8 days), for which reason radon entering buildings usually originates from the upper few meters of the soil. In addition, radon dissolves within water contained in the soil pores and adsorbs onto soil grains [1]. The latter has been reported to significantly reduce radon migration fluxes in dry soils since vapor adsorption in these cases takes place directly on the grain surfaces [10-14].

Inside buildings ventilation and stack effects usually cause the air pressure to be lower than in the surrounding soil. This results in a pressure gradient across the foundation ranging from 2 to 10 Pa, but it may be as high as 15 Pa during the heating season [15]. As a result, advective air movement transports radon and other soil vapors adjacent to the building's substructure through the zone of influence with a flux highly exceeding what is achieved by diffusion alone [16-19]. Even though the zone of influence plays a critical role for radon intrusion to indoor air, a clear definition is still not available. Nor is the connection between its depth and characteristics of the construction and soil present at the site described [20-22].

It is believed that studies addressing radon migration in soil will likely benefit from the intensive research conducted on organic soil vapor transport over the past two decades. In this respect, one of the worlds leading groups has been the Aalborg University-Århus University collaboration who has contributed with a large number of significant publications within risk assessment, soil physics, vapor transport and sorption of chemicals in unsaturated soil. Qualifications of the research group including the main applicant are given in Enclosure 5.

Research plan

The project is divided into three work-packages (WP's) focusing on the underlying key factors governing radon gas migration beneath buildings in or near the advective zone of influence. Collectively, these studies will provide a thorough conceptual understanding of the system described in Fig. B and will allow for informed evaluation of potential radon entry to indoor environments. Each WP is described below:

WP1 **Radon gas diffusion and adsorption beneath buildings.** *"Do low-moisture conditions in soil underlying constructions increase the importance of radon diffusion and adsorption?"* Compared to transport by advection, radon gas-phase diffusion and adsorption onto soil grains are traditionally assumed to be negligible when assessing migration to indoor environments [1]. However, recent studies suggest that moisture contents in soil underlying buildings may be reduced compared to soil external to the building, causing an order-of-magnitude increase in the flux caused by diffusion [23]. Furthermore, these dryer soils, that are often highly compacted, may provide a large surface area on which radon can adsorb directly to the soil grains [12-14].

I wish to make use of and further develop models proposed for organic vapor transport to evaluate potential diffusion and adsorption of radon in soils underlying buildings. A simple analytic-stochastic model approach will be proposed and applied to estimate the likely diffusion and adsorption for varying moisture conditions. The model will account for natural geologic variability using so-called Monte-Carlo simulations (repeated random sampling). The model will be validated using existing field data.

Applied perspective of WP 1

- A simple and validated analytic-stochastic risk model for prediction of radon diffusion towards buildings. This will provide the opportunity, in a simple way, to consider diffusive contributions to indoor radon intrusion.

WP2 **Radon gas advection under fluctuating air pressure.** *"What is the effect of naturally occurring pressure fluctuations on the advective zone of influence?*" The zone of influence within which advection of radon will be dominant is assumed to vary in depth and width as a result of atmospheric and wind-induced pressure fluctuations and changes in indoor air pressure [20, 24-27]. However, the direct relation between pressure propagations and soil characteristics remains unknown [9].

The effect of pressure fluctuations, soil layering and soil moisture content will be investigated based on laboratory soil column experiments. In these, the within-column pressure and tracer gas concentrations (N_2O and O_2) are monitored using extraction of air samples and sensitive pressure sensors while applying a varying air pressure above the soil column. A variety of soil materials will be used, ranging from gravel to silt and clay. Based on experimental data, the relation between soil characteristics and depth of the zone of influence will be evaluated. The column experiments in this study will be based on a setup available at Århus University (AU).

Applied perspective of WP 2

- Empirical relationships between soil parameters and depth of the advective zone of influence. These will allow for estimation of the zone of influence from easily obtainable data such as soil type and moisture content.

WP3 **Field validation of conceptual model of radon intrusion.** *"How deep is the zone of influence and what is its relation to radon concentrations in soil and indoor air?"* The depth of the advective zone of influence is reported to range from 1 to 2 meters beneath a building's slab [17, 28]. However, the number of field studies is very limited, and most vapor intrusion models build on rather unconfirmed assumptions about the final vapor transport to the underneath of the building's substructure [17, 20].

We will perform a field study of vapor transport beneath and into a building located in an area with elevated subsurface radon concentrations. Furthermore, the field site is contaminated with volatile pollutants, allowing for a comparison between transport mechanisms of pollutants and radon, which has not been done before. Measuring and sampling equipment will be installed in the outdoor air, in different depths beneath the building's substructure, and inside the building during a period of 3-4 months. Radon concentrations and the total air pressure will be monitored and data from soil and indoor air will be compared. The radon intrusion flux will be estimated and depth and width of the zone of influence will be determined. This study will provide unique field data and allow for validation of the conceptual understanding of radon transport through soil and across building foundations. Results will be compared to model and laboratory data from WP 1 and 2. The field work will be arranged in collaboration with experts from Rambøll Sweden and assisted by Rambøll technicians.

> **Applied perspective of WP 3**
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> - Validation of models predicting the zone of influence and the radon entry rate under field conditions. Radon results will be compared with pollutant vapor migration at the same site to indentify similarities and differences in the vapor behavior.

Project timeline and publication plan

Below timeline describes project activities during the three-year project period. It is noted that I apply for PostDoc funding only covering 18 months (i.e. half-time employment). Expected publications (A-F) are included in the bottom lines. They comprise of three peer-reviewed publications, two conference proceedings, and one popular scientific journal article.

Task	Year 1		Year 2		Year 3	
Start-up phase/international meetings						
"Radon" homepage (electronic knowledge portal and project information) in the air						
Purchase and test of radon field measuring equipment						
Meetings and field trips with project partners in Rambøll Sweden						
Publication	A					
Purchase and test of radon field measuring equipment						
WP1: Radon gas diffusion and adsorption beneath buildings (AAU)						
Model development and validation						
Publication of results		B	C			
WP2: Radon gas advection under fluctuating air pressure (AAU and AU)						
Laboratory experiments						
Data treatment						
Publication of results				D		
WP3: Field validation of conceptual model of radon intrusion (AAU and Rambøll)						
Large field experiment						
Data treatment						
Publication of results						E,F

EXPECTED PUBLICATIONS	
A (conference proc.)	Experiences with Radon Risk Evaluation and Prevention across the Scandinavian Countries. Proceedings of NORDROCS 2010 (International conference)
B (popular)	Gasdiffusion i byjord: Betydning for indtrængning af radon og forurening til indeklimaer. Vand & Jord (Danish popular scientific journal)
C (peer reviewed)	**Simple semi-analytical model for predicting vapor migration distances from a radon source at varying moisture conditions. Journal of environmental engineering**
D (peer reviewed)	**Effect of pressure fluctuations on vapor transport in a soil column. Vadose zone journal**
E (peer reviewed)	**Pressure-driven radon transport beneath and into a slap-on-grade building: A field study. Environmental science & technology**
F (conference proc.)	Influenszone under bygninger: betydning for indtrængning af radon og forurening til indeklima. Proceedings of ATV-Jord og Grundvand's annual meeting (Danish engineering conference)

References

1. Nazaroff, W. W., Radon transport from soil to air. *Rev. Geophys.* **1992,** *30*, (2), 137-160.
2. Darby, S.; Hill, D.; Auvinen, A.; Barrios-Dios, J. M.; Baysson, H.; Bochicchio, F.; Deo, H.; Falk, R.; Forastiere, F.; Hakama, M.; Heid, I.; Kreienbrock, L.; Kreuzer, M.; Lagarde, F.; Makelainen, I.; Muirhead, C.; Oberaigner, W.; Pershagen, G.; Ruano-Ravina, A.; Ruosteenoja, E.; Rosario, A. S.; Tirmarche, M.; Tomasek, L.; Whitley, E.; Wichmann, H. E.; Doll, R., Radon in homes and risk of lung cancer: Collaborative analysis of individual data from 13 european case-control studies. *Br. Med. J.* **2005,** *330*, (7485), 223-226.
3. Andersen, K. A., Svensker: Vi er langt foran Danmark med radonsikring. *Ingeniøren* November 14, 2009.
4. DKEPA *Status og perspektiver på indeklimaområdet*; Danish Environmental Protection Agency: 2006.
5. Andersen, C. E.; Bergsoe, N. C.; Majborn, B.; Ulbak, K., Radon and natural ventilation in newer danish single-family houses. *Indoor Air - International Journal of Indoor Air Quality and Climate* **1997,** *7*, (4), 278-286.
6. Andersen, C. E., Numerical modelling of radon-222 entry into houses: An outline of techniques and results. *Sci. Total Environ.* **2001,** *272*, (1-3), 33-42.
7. Schroede.Gl; Kraner, H. W.; Evans, R. D., Diffusion of radon in several naturally occurring soil types. *Journal of Geophysical Research* **1965,** *70*, (2), 471-&.
8. Garbesi, K.; Sextro, R. G.; Robinson, A. L.; Wooley, J. D.; Owens, J. A.; Nazaroff, W. W., Scale dependence of soil permeability to air: Measurement method and field investigation. *Water Resour. Res.* **1996,** *32*, (3), 547-560.
9. Garbesi, K.; Robinson, A. L.; Sextro, R. G.; Nazaroff, W. W., Radon entry into houses: The importance of scale-dependent permeability. *Health Phys.* **1999,** *77*, (2), 183-191.
10. Olesen, T.; Gamst, J.; Moldrup, P.; Komatsu, T.; Rolston, D. E., Diffusion of sorbing organic chemicals in the liquid and gaseous phases of repacked soil. *Soil Sci. Soc. Am. J.* **2001,** *65*, (6), 1585-1593.
11. Petersen, L. W.; ElFarhan, Y. H.; Moldrup, P.; Rolston, D. E.; Yamaguchi, T., Transient diffusion, adsorption, and emission of volatile organic vapors in soils with fluctuating low water contents. *Journal of Environmental Quality* **1996,** *25*, (5), 1054-1063.
12. Petersen, L. W.; Moldrup, P.; Elfarhan, Y. H.; Jacobsen, O. H.; Yamaguchi, T.; Rolston, D. E., The effect of moisture and soil texture on the adsorption of organic vapors. *Journal of Environmental Quality* **1995,** *24*, (4), 752-759.
13. Petersen, L. W.; Rolston, D. E.; Moldrup, P.; Yamaguchi, T., Volatile organic vapor diffusion and adsorption in soils. *Journal of Environmental Quality* **1994,** *23*, (4), 799-805.
14. Schery, S. D.; Lopez, T. L., Measurements of the sorption of radon on porous materials. *Abstracts of Papers of the American Chemical Society* **1989,** *198*, 24-I&EC.
15. Hers, I.; Zapf-Gilje, R.; Li, L.; Atwater, J., The use of indoor air measurements to evaluate intrusion of subsurface voc vapors into buildings. *J. Air Waste Manage. Assoc.* **2001,** *51*, (9), 1318-1331.
16. Nazaroff, W. W.; Feustel, H.; Nero, A. V.; Revzan, K. L.; Grimsrud, D. T.; Essling, M. A.; Toohey, R. E., Radon transport into a detached one-story house with a basement. *Atmos. Environ.* **1985,** *19*, (1), 31-46.
17. USEPA *User's guide for evaluating subsurface vapor intrusion into buildings* United States Environmental Protection Agency: Washington, D.C. 20460, 2004.
18. Keskikuru, T.; Kokotti, H.; Lammi, S.; Kalliokoski, P., Effect of various factors on the rate of radon entry into two different types of houses. *Build. Environ.* **2001,** *36*, (10), 1091-1098.
19. Andersen, C. E.; Sogaard-Hansen, J.; Majborn, B., Soil-gas and radon entry into a simple test structure - comparison of experimental and modeling results. *Radiat. Prot. Dosim.* **1994,** *56*, (1-4), 151-155.
20. USEPA *Review of recent research on vapor intrusion* U. S. Environmental Protection Agency: Washington, D. C., 2005.
21. Abreu, L. D. V.; Johnson, P. C., Effect of vapor source - building separation and building construction on soil vapor intrusion as studied with a three-dimensional numerical model. *Environ. Sci. Technol.* **2005,** *39*, (12), 4550-4561.
22. Patterson, B. M.; Davis, G. B., Quantification of vapor intrusion pathways into a slab-on-ground building under varying environmental conditions. *Environ. Sci. Technol.* **2009,** *43*, (3), 650-656.

23. Tillman, F. D.; Weaver, J. W., Temporal moisture content variability beneath and external to a building and the potential effects on vapor intrusion risk assessment. *Sci. Total Environ.* **2007,** *379*, (1), 1-15.
24. Riley, W. J.; Gadgil, A. J.; Bonnefous, Y. C.; Nazaroff, W. W., The effect of steady winds on radon-222 entry from soil into houses. *Atmos. Environ.* **1996,** *30*, (7), 1167-1176.
25. Riley, W. J.; Gadgil, A. J.; Nazaroff, W. W., Wind-induced ground-surface pressures around a single-family house. *Journal of Wind Engineering and Industrial Aerodynamics* **1996,** *61*, (2-3), 153-167.
26. Riley, W. J.; Robinson, A. L.; Gadgil, A. J.; Nazaroff, W. W., Effects of variable wind speed and direction on radon transport from soil into buildings: Model development and exploratory results. *Atmos. Environ.* **1999,** *33*, (14), 2157-2168.
27. Robinson, A. L.; Sextro, R. G.; Riley, W. J., Soil-gas entry into houses driven by atmospheric pressure fluctuations - the influence of soil properties. *Atmos. Environ.* **1997,** *31*, (10), 1487-1495.
28. Garbesi, K.; Sextro, R. G.; Fisk, W. J.; Modera, M. P.; Revzan, K. L., Soil-gas entry into an experimental basement - model measurement comparisons and seasonal effects. *Environ. Sci. Technol.* **1993,** *27*, (3), 466-473.