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DESIGN AND DEVELOPMENT OF A PRESSURE SENSITIVE HVAC UNBALANCED PRESSURIZATION CONTROLLER (HUPC) SYSTEM FOR MINIMIZING INDOOR RADON CONCENTRATIONS IN SLAB-ON-GRADE STRUCTURES

Kaiss K. Al-Ahmady and David E. Hintenlang
Department of Nuclear Engineering Sciences
University of Florida
Gainesville, FL 32611

Arthur Kozik and Paul Oppenheim
M.E. Rinker School of Building Construction
University of Florida
Gainesville, FL 32611

ABSTRACT

The highest time-averaged indoor radon concentrations for a slab-on-grade structure occur when the structure experience neutral pressure conditions. Experimental evidence was provided throughout the utilization of the University of Florida Radon Research House (UFRRH) showing that semi-diurnal atmospheric pressure variations are responsible for continuous pumping of radon-rich soil gas into the structure which elevates indoor radon concentrations. A pressure sensitive HVAC controller system was designed to minimize the indoor radon concentrations. The HVAC Unbalanced Pressurization Controller (HUPC) system accommodates for the semi-diurnal pumping of radon and the transient changes in barometric pressure. The system is capable of initiating HVAC unit ventilation during the OFF thermostat position of the HVAC operating cycle. The system is designed to operate with two basic features: performing variable-in-time triggering functions and creating controlled HVAC positive ventilation. This HUCP concept may utilize to reduce indoor Rn concentrations from 2000 Bq m^{-3} to less than 120 Bq m^{-3} that have observed with continuous fan ventilation at the UFRRH . Two HUPC system designs were developed including one with a simple mechanical system alteration to the HVAC duct system.

INTRODUCTION

The transport of Radon (Rn) from the sub-structure area into residential structures can be described by convective and molecular diffusion processes. Pressure driven air flow is the principle mechanism for radon entry into the interiors. Pressure differences generated from the interactions between the indoor, outdoor and sub-structure area being under different environmental and occupation conditions are responsible for elevated indoor radon concentrations. Recent studies have given a major influence to the transient behavior associated with barometric pressure changes. Hintenlang and Al-Ahmady have demonstrated experimental evidence that semi-diurnal pressure differential driven radon entry exists for a slab-on-grade structure built over low permeability soil. Mathematical treatments predicting the sub-slab air volume pressures and the pressure differentials across the slab have been correlated to the atmospheric tidal barometric pressure variations and are found to be responsible for significant increases in indoor radon concentrations [Al-Ahmady 1992, Hintenlang and Al-Ahmady 1992]. Other investigators have also shown that transient atmospheric changes associated with changing meteorological conditions contribute to radon transport [Tsang and Narasimhan 1992, Harley and Chittaporn 1992, Narasimhan et al. 1990, Owczarski et al. 1990, Clements and Wilkening 1974].

Increased building pressure has long been identified as an effective technique to change indoor radon concentrations. However, this technique is not always practical. House depressurization contributes to increased radon entry rates by increasing the pressure-driven flow of radon-containing soil gases into the interiors. Typical sources of house depressurization that have previously been investigated include wind and temperature effects, stack effects, and mechanical depressurization of a structure by household appliances including heating, ventilating and air-conditioning (HVAC) systems [Nazaroff et al. 1988, Nero 1988, Nazaroff et al. 1987]. Observations of temperature dependence on pressure differences have shown in many cases that indoor radon concentrations exhibit a diurnal cycle [Gesell 1983]. Furrer et al. reported strong, long term correlations between the temperature differences and pressure differences that exist between the indoor and outdoors [Furrer et al. 1991]. Al-Ahmady and Hintenlang have demonstrated that temperature induced pressure differences can be a significant influence on radon driving forces and consequently the indoor radon concentrations under particular configurations associated with the utilization of the HVAC system [Al-Ahmady and Hintenlang 1993]. The effects of air infiltration rates, that are governed by the differential pressure across the structure shell, on indoor radon concentrations can be attributed to the exchange and dilution of indoor radon with ambient air having much lower radon concentrations. Recent studies indicate that manipulation of the air exchange rates associated with the HVAC system operation can reduce indoor radon concentrations under neutral pressure conditions. It has been demonstrated that increasing house ventilation rates by increasing the effective leakage area of the house shell does not reduce indoor radon concentrations as effectively as increasing house ventilation by controlling duct ventilation associated with HVAC system operation [Hintenlang and Al-Ahmady 1993a].

In this work, we integrate a previously developed radon driving force model [Hintenlang and Al-Ahmady 1992] into a temperature induced pressure difference model [Al-Ahmady and Hintenlang 1993] to calculate indoor radon driving forces associated with the HVAC system operation under different environmental conditions. Mathematical treatments are utilized to reduce the expressions into a single control design equation associated with the controlled duct ventilation for the HVAC system. The control design equation is employed in the process of developing the two systems that can reduce indoor radon concentrations.

The data presented were collected on a dedicated research house, operated by the University of Florida. The University of Florida Radon Research House (UFRRH) is part of the Florida Radon Research Program (FRRP). The research house was carefully chosen and heavily instrumented with a variety of devices. Thus, a number of key parameters could be measured or monitored simultaneously. The research house effort by the University of Florida is dedicated towards the development of radon resistant building codes for Florida houses and designated to provide detailed characterization of the effects of HVAC induced radon entry and modeling of the radon entry and transport.

METHODOLOGY

Continuous measurements have been designed to monitor the time and special dependent responses of the temperature, pressure, air flow, radon concentrations, weather parameters, and HVAC operation parameters at the UFRRH. The house is an unoccupied one-story residential structure and has a floor area of 163 m^2, indoor air volume of 400 m^3, concrete slab-on-grade, concrete block stemwall foundation, and has a 10.1m x 16.2m footprint. The temperature, pressure, and air flow data are collected using analog and thermocouple input boards integrated to a Keithley Metrabyte micro-channel driver card. A Setra 270 barometric pressure transducer (600-1100 mbar range) is installed at the site and integrated to the Metrabyte data acquisition and control system. The Metrabyte system is interfaced and fully controlled by an IBM PS/2 computer system.

The pressure differential measurements across the house walls, slab, and indoor locations are performed utilizing very low range Setra C264 differential pressure transmitters of ±25 Pa. full scale and minimum sensitivity of less than ±0.25 Pa. An array of sixteen pressure transmitters are distributed across the slab in a uniform 4.88m x 2.74m grid pattern. These transmitters monitor the differential pressure above and below the concrete slab through standard (3/16 in.) 4.7 mm I.D. tubes that provide access to the sub-slab area at each grid point.

Indoor/outdoor pressure differences are produced by a calibrated-fan, Minneapolis blower door, over a range of 2-50 Pa; and the HVAC positive ventilation system over a range of 0-3 Pa. These operations are also utilized to quantify infiltration air and air exchange rate for the house using the ASTM standard blower door protocol [ASTM 1987]. Supply and return duct flow rates are performed using a flow hood in addition to the air flow transducers that are integrated to the Metrabyte system for each experimental configurations.

All the exterior pressure ports (for barometric pressure and those penetrating the walls) are covered by a perforated, hollow sphere to dampen rapid pressure variations caused by wind gusts. The measurements between the outdoor and the sub-slab are carried out utilizing a T-type connector to one of the sub-slab points. The transmitters are connected to the Metrabyte system using an Omega switch board to provide flexibility during calibrations or to run the measurements at specific slab points as needed.

Temperature is monitored in each room, the supply and return ducts, room register, HVAC thermostat location, attic, sub-slab area and outdoors using T-type, Copper vs. Copper-Nickel, thermocouple wires. The Metrabyte thermocouple board cold junction temperature is regularly calibrated at the beginning of each measurement period. The weather parameters such as wind speed, wind direction and rainfall data are collected utilizing a datalogger integrated with a meteorological station located on the site. The datalogger data are remotely collected for processing.

Time-integrated indoor radon concentrations measurements are performed using AT-Ease, E-PERM, and Pylon radon measuring systems. The time dependent radon measurements are performed using Pylon AB-5 portable radon monitors utilizing the passive radon detector cell (PRD-1 and CPRD). The Pylon counts are accumulated over a time interval, stored in the monitor memory at the end of each interval and downloaded to an IBM PC at the conclusion of the experimental period.

Experimental period of typically 96 hours and measurement interval of 60 seconds, averaged every 600 seconds has been used to perform the measurements. These test periods provide suitable time to monitor the transient response in the house system as well as after the house system has stabilized. The same experimental protocol is followed for each experimental period. Experiments typically consist of performing zero checks on all instrumentation, setting the desired differential pressure using the blower door/HVAC system, and monitoring the device outputs over the duration of the experiments.

RESULTS AND DISCUSSION

Fig. 1 shows the observed average indoor radon concentrations at the UFRRH as a function of the magnitude of whole house pressure conditions. The experimental data in the figure represent the average indoor Rn concentrations for a 48-hour interval after these concentrations reach equilibrium for each pressurization and depressurization level. The highest concentrations of indoor radon occur when the structure undergoes neutral pressure conditions. Pressure differentials between the indoor and outdoors, $\Delta P_{i/o}$, of values less than 1 Pa are usually associated with these neutral pressure conditions when the other sources of mechanical pressurization or depressurization do not exist. Semi-diurnal atmospheric tidal barometric pressure variations are responsible for driving radon-rich soil gas from the sub-structure area into the interior and consequently causing elevated indoor radon concentrations under neutral pressure conditions. The sub-slab soil system below the foundation limits soil gas velocities and causes the sub-slab air volume pressure to experience a delayed response to changes in atmospheric pressure. These transient effects of barometric pressure changes on radon entry and concentrations are being increasingly recognized as an important driving force of radon into residential structures.

Fig. 2 illustrates the semi-diurnal pressure differentials measured across the structure slab, ΔP_{slab}. Pressure difference values near the center of the slab are typically around 5 Pa. Elevated indoor radon concentrations are found to be generated due to the semi-diurnal natural pumping of soil gas into the interior and severe limitations on the air exchange rate across the structure shell under neutral pressure conditions.

Careful examination of Fig. 1 suggest that slightly pressurized or depressurized conditions could provide significant reduction in indoor radon concentrations. A particular pressure range, between -10 to 10 Pa, seems to consequentially minimize indoor Rn concentrations, with more reduction being observed on the pressurization side. This critical range of indoor pressure conditions is usually associated with the utilization of HVAC systems and some other house appliances. Hintenlang and Al-Ahmady have shown how the semi-diurnal naturally occurring radon entry can be reduced by HVAC operation [Hintenlang and Al-Ahmady 1993b]. They have developed radon entry and concentration modeling to simulate the operation of the HVAC system in residential structures. A previous radon concentration model that successfully predicted the average indoor radon concentrations was being used to study the effects of several parameters on radon entry. Simulations were performed for different diffusion entry rates, different air exchange rates that are developed utilizing the HVAC system ventilation and changing the structure's effective leakage area. It has been demonstrated that increasing the house ventilation rate by increasing the effective leakage area of the house shell does not reduce indoor radon concentrations as effectively as increasing house ventilation rates by controlling duct ventilation associated with the HVAC system [Hintenlang and Al-Ahmady 1993a].

Further investigations indicate that controlled duct ventilation applications that provide positive ventilation, in which indoors is slightly pressurized the relative to the outdoors, provides better reduction of indoor radon concentrations compared with balanced ventilation [Hintenlang et al. 1993]. Fig. 3 illustrates the reduction of indoor radon concentration associated with controlled duct ventilation for several air exchange rates. In order to utilize these findings several considerations are taken into account to develop a design control equation that can be used in controlling the positive ventilation in the HVAC system. The system required to provide and perform this control, must be a pressure sensitive device that unbalances the HVAC system according to pressure considerations. Temperature effects, differential pressure across the slab, barometric pressure and the differential pressure between the indoor and outdoor have to be considered in the design of a pressure sensitive HVAC Unbalanced Pressurization Controller (HUPC) system for minimizing indoor radon concentrations.

It is important to note that the temperature differences between the indoor and outdoor could seriously disturb the indoor pressure patterns in a small pressure span around zero Pa. Fig. 4 shows the time variance of differential pressures between indoors and outdoors and between the indoor and sub-slab area. The two differential pressure responses do not appear to be coupled to each other. The pressure differential response between the indoors and outdoors demonstrates a diurnal cycle with a peak amplitude of about 0.4 Pa. These are attributed to the varying temperature differences between indoor and outdoor environments that occur throughout the day. Under neutral pressure conditions these responses are small in magnitude because temperature differences between the indoor and outdoor remain small during the time when these experiments were performed. Also, the house is well sheltered from the wind. Pressure differences induced by winds across the structure could have profound influence for the critical indoor pressure span around zero pascal. However, the minimal contribution of wind effects during the performing of these experiments are verified by the weather station mounted on the structure and the indoor/outdoor differential pressure monitors mounted on two opposite sides of the house. The anemometer indicated wind speeds less than 0.18 m s^{-1} greater than 90% of the time and the indoor/outdoor pressure responses measured across the different walls were observed to be nearly identical in phase throughout the experimental periods. This demonstrates that the influence of wind induced imbalances during these experiments are negligible.

Al-Ahmady and Hintenlang have linearly combined the pressure differences between the indoor and outdoor that are induced by indoor/outdoor temperature differences. Their studies provide experimental evidence and theoretical modeling that lends support to the diurnal temperature induced pressure differentials between the indoor and outdoor under neutral pressure conditions and other conditions associated with the operation of the HVAC systems. Fig. 5 illustrates the temporal variation pressure differences induced by the temperature differences between the indoor and outdoors over a 48-hour period at the UFRRH under moderate temperature and low wind weather conditions. It has been demonstrated that the pressure differences induced by temperature differences, between indoor and outdoors, are directly proportional to both the magnitude of the temperature difference and the average temperature between the indoor and outdoor [Al-Ahmady and Hintenlang 1993].

The blower door measurements are utilized to characterize the required volumetric flow rate that must be induced to maintain the interior at a given pressure measured relative to outdoors. These measurements are performed at selected time intervals when the indoor and outdoor temperatures are approximately equal and constant. These measurements are applied to provide indoor/outdoor pressure differences that are only developed by the induced air and are isolated from the temperature induced pressure differences. The measurement procedure follows the standard ASTM blower door testing protocol and the empirical fit to the collected data provides,

$$\Delta P_{i/o,I} = \exp[1.44 \ln(Q/79.76)] \qquad (1)$$

where $\Delta P_{i/o,I}$ is the pressure differential generated between the indoor and outdoor generated by the induced fresh air (Pa), and Q is the induced fresh air volumetric flow rate (m^3 s^{-1}). Fig. 6 shows the relation between the pressure differences and the flow rate over a small range of the house pressure conditions. The relation can be approximated as straight line and extrapolation to smaller pressure differences that simulate the HVAC operation is utilized. Experimental verifications using the pressure transducers that are distributed over the slab indicate similar values of induced indoor pressure. Also eqn. 1 is independent of the position where the induced fresh air occurs, this permits the utilization of eqn. 1 for the induced fresh air developed by the HVAC system.

The pressure differences between indoor and outdoors that are induced by temperature differences, $\Delta P_{i/o,T}$, are previously modeled based on a linear approximation of the weekly exponentially dependent pressures between two different temperatures under hydrostatic equilibrium [Al-Ahmady and Hintenlang 1993] as,

$$\Delta P_{i/o,T} = P_o\, C\, [(T_i - T_o)/T_i T_o] \qquad (2)$$

where P_o is the atmospheric pressure at sea level (10^5 Pa). C is a constant which has been previously calculated as 0.0477 K [Al-Ahmady and Hintenlang 1993], and T_i, T_o are the indoor and outdoor temperatures (K), respectively. If pressure differences due to the induced fresh air and temperature are linearly combined with their partial weight normalized to one, the indoor/outdoor pressure differential is then,

$$\Delta P_{i/o}= \Delta P_{i/o,I} + \Delta P_{i/o,T} + B\ \Delta P_{i/a} \qquad (3)$$

where $\Delta P_{i/a}$ is the pressure difference between the indoor and attic zones. B is a constant that characterizes the partial contribution of pressure differences that might exist between the attic and indoor zone due to leakage in the HVAC duct system and different temperature zones. Leakage in the supply duct system in the attic area can depressurize the house interior compared to the situation when no leakage exists. The attic area may be pressurized if the leakage rate exceeds the rate of exfiltrated air into the outdoors through the attic vents. A portion of this air may return to the interior in proportion to the constant B. The value of the constant B is therefore dependent on the characterization of the attic area interface with the interior and the ceiling integrity for an individual structure. This contribution can be remarkable especially for cases when duct leaks are not sealed or large gaps exist between the ducts and registers. This contribution is highly dependent on the duct system installation practices as well as different attic zone temperatures which are usually on a different track than the indoor. The UFRRH duct system, including supply and return, are well sealed to minimize the leakage into and from the attic area. Differential pressure transducers monitoring the pressure difference between the indoor and attic area indicate a minimal difference that can be attributed to temperature differences. Visual inspection of the house/ceiling integrity indicate that B should be very small. Therefore, the third term of eqn. 3 is assumed to be approximately zero for this application.

Pressure differentials across the structure slab can be estimated as $\Delta P_{slab}=P_{ss}-P_{in}$, and pressure differences between the indoor and outdoors can be written as $\Delta P_{i/o}=P_{in}-P_{out}$. The outdoor pressure is the barometric pressure, P_b, and therefore the indoor pressure becomes,

$$P_{in}=\Delta P_{i/o}+P_b \qquad (4)$$

the sub-slab air volume pressure, P_{ss}, was modeled as an exponentially damped response to the changes in barometric pressure [Hintenlang and Al-Ahmady 1992]. The delay in the sub-structure soil volume is a function of the geometric location under the slab. For the current application, a geometric location that produces the maximum differential pressure across the slab is chosen, which is usually located near the center of the slab. The sub-slab air volume pressure can be calculated by,

$$P_{ss}=P_b-[P_b-P_{ssp}]\exp(-\Delta t/t_m) \qquad (5)$$

where P_{ssp} is the sub-slab air volume pressure at the previous time interval, ΔT, that depends on the barometric pressure changes and t_m is the maximum delay time of the sub-structure soil system pressure to equalize with the barometric pressure. Utilizing eqns. 4 and 5, the pressure differential across the slab can be calculated as,

$$\Delta P_{slab}=(P_{ssp}-P_b)\exp(-\Delta t/t_m)-\Delta P_{i/o} \qquad (6)$$

This pressure differential is the major contributor of pressure driven radon entry, the convective component of radon transport into structures. Other radon entries can be represented by the diffusion component and convective component from outdoor into indoor. The later two components are small compared with the convective transport from the sub-structure area into the interior. The minimal contributions of these two components are offset by the utilization of a safety design factor in the HUPC system.

Implementing eqn. 6 as the design control parameter in the process of developing the required quantity of induced fresh air under positive ventilation, the design required that,

$\Delta P_{i/o} >= \Delta P_{slab}$, and therefore,

$$\Delta P_{i/o}= D_c >= 0.5\ f_s\ (P_{ssp}-P_b)\exp\ (-\Delta t/t_m) \qquad (7)$$

where f_s is the safety design factor and has a value of (>=1.0), and D_c is the design control parameter.

It is important to note that P_{ssp} is the previous sub-slab air volume pressure prior to the current change in barometric pressure. The value of this pressure is the same as barometric pressure P_b after the sub-slab air volume pressure reaches equilibrium. Therefore the quantities P_{ssp}, P_b are measured against the same parameter (barometric pressure) with time interval of Δt. The barometric pressure observations at the research structure indicate temporal variations are significantly slower than the time interval required to stabilize the sub-slab air volume pressure with the barometric pressure changes. This reflects the fact that the value of Δt exhibited by the barometric pressure behavior is significantly larger than the maximum equilibrium time of the sub-structure soil system near the center of the slab, $\Delta t >> t_m$, most of the time. An analysis of the design control parameter equation indicates that D_c is equal to zero when no change in the barometric pressure occurs after Δt, and has a negative value when the barometric pressure exhibits an increase in its value over the consecutive time interval. Both cases require no-action by the HUPC system on the operation of the HVAC system. These cases match the experimental observations and the theoretical predictions when the sub-slab soil system exhibits slower response to the increasing changes in barometric pressure. At the same time the indoor pressure responds much faster leaving the indoor pressurized compared to the sub-slab area. The value of the exponent in the design control eqn 7, then, can be treated as a constant. A minimum Δt is chosen that is limited by the mechanical system time response to fully developed the required Q for changes in barometric pressure. t_m value could range from less than one to about 20 minutes depending upon the soil system, slab geometry, and slab size. For this application a value of 12 min. is chosen based on observations at the UFRRH, and a value of Δt=2 min. is applied. It is important to note that this practice introduces a larger safety factor into the required indoor/outdoor pressure difference that must be developed by the system to minimize indoor radon concentrations. The design equation becomes,

$$D_c = F_s\,(P_{ssp} - P_b) \qquad (8)$$

where $F_s = 0.4\ f_s$, is the overall design factor.

Fig. 7 illustrates an application of the HUPC system design. A simple modification to the duct system can be made to accommodate this application. A barometric pressure port can be installed and connected to a damper on the return duct before the HVAC blower which is open to the atmosphere on the outside end. The return duct damper is designed to be a mechanically balanced enclosure that can be moved by a rod connected to a barometric pressure piston. The piston movements are allowed only in the direction that corresponds to the decreases in barometric pressure. The damper enclosure position is calibrated with the range of the required flow rate to the interior. The damper position creates access to the ambient environment and the fresh air is induced into the system by the depressurization on the blower intake side. This configuration provides a calibrated quantity of fresh air to pressurize the interior providing positive ventilation. The control rod between the damper and the barometric pressure piston has a double-sided electromagnetic (EM) relay switch that supplies power to the HVAC blower when the thermostat is in the OFF position. The relay is activated once the damper moves from the full closed position. This switch initiates the HVAC system without influence from the cooling or heating load. For some particular cases when the barometric pressure is not sufficient to produce enough force to move the damper, the piston assembly can be replaced with a servo-system to move the damper. The servo-system then is controlled by a pressure transducer. The application of the controlled induced fresh air positive pressure ventilation implemented by the HUPC concept and design is expected to be remarkably successful in minimizing indoor radon concentrations. Continuous positive ventilation of about 0.047 m^3 per sec, supplied by the UFRRH 2.5 ton HVAC circulation fan, was able to reduce indoor radon concentrations form about 2000 Bq m^{-3} (54 pCi l^{-1}) to less than 120 Bq m^{-3} (3.2 pCi l^{-1}).

A more complicated system could be applied to the HUPC design and operation. This include the installation of an auxiliary fan on a barometric pressure access duct to the utilization of electronic controls and microprocessors. In the case of auxiliary fan installation, a parallel connection is made from the EM triggering switch to provide power to the auxiliary fan motor. Two EM switches can be employed to provide different trigger timing to the auxiliary fan and the main HVAC blower if needed. This installation gives the flexibility to trigger the auxiliary fan at a specific volumetric flow rate when the required rate provided by the HVAC blower is no longer sufficient. Partial level combinations between these two blowers, or among more than two induced air providers, could be utilized based on designated ranges of the required volumetric flow rates to manage better system performance and/or energy considerations for more complicated structures and indoor radon problems. The system could also use a heat exchanger unit that might utilize built in supplementary fan for increased efficiency. Fig. 8 illustrates a schematic diagram that employs a more sophisticated utilization of the design control equation with feed back applications. A barometric pressure and differential pressure transducer provide continuous analog signals to a microprocessor control device. The microprocessor calculates the value of the time interval Δt by scanning the barometric pressure channel signal at some selected scan rate. The differential pressure transducer that mounts between the indoor and outdoor provides a signal that feeds back to the program to adjust the amplitude of the control signal to the return duct damper. The duct damper position is moved by a step motor controlled by the microprocessor.

CONCLUSIONS

Remarkable reduction of indoor radon concentrations can be achieved through design utilization of the Heating, Ventilating and Air-Conditioning systems. Induced fresh air from the outdoor into the indoor by the HVAC blowers and/or auxiliary fans can be utilized to provide slight pressurization of the indoor compared to the outdoors and increase the air exchange rates throughout the structure. HVAC system operations that provide positive pressure ventilation throughout the structure significantly reduce indoor radon concentrations by increasing the air exchange rate throughout the entire structure. The air exchange rate increases developed by increasing the structures effective leakage areas is not as effective as increases developed by positive ventilation. The HVAC positive pressure ventilation provided through the design concept and application of the pressure sensitive HVAC Unbalanced Pressurization Controller (HUPC) System are capable of providing designated control over the HVAC operation. Such control includes adjustable induction of fresh air into the depressurized side of the HVAC blower which creates positive structure ventilation that increases the air exchange rates and slightly pressurize the structure. The HUCP design concept can be implemented through simple mechanical system alternations, which can control the fresh air supply damper corresponding to transient changes in barometric pressure. More complicated systems can provide sophisticated control over the ventilation system for more complex structures and/or indoor radon problems.

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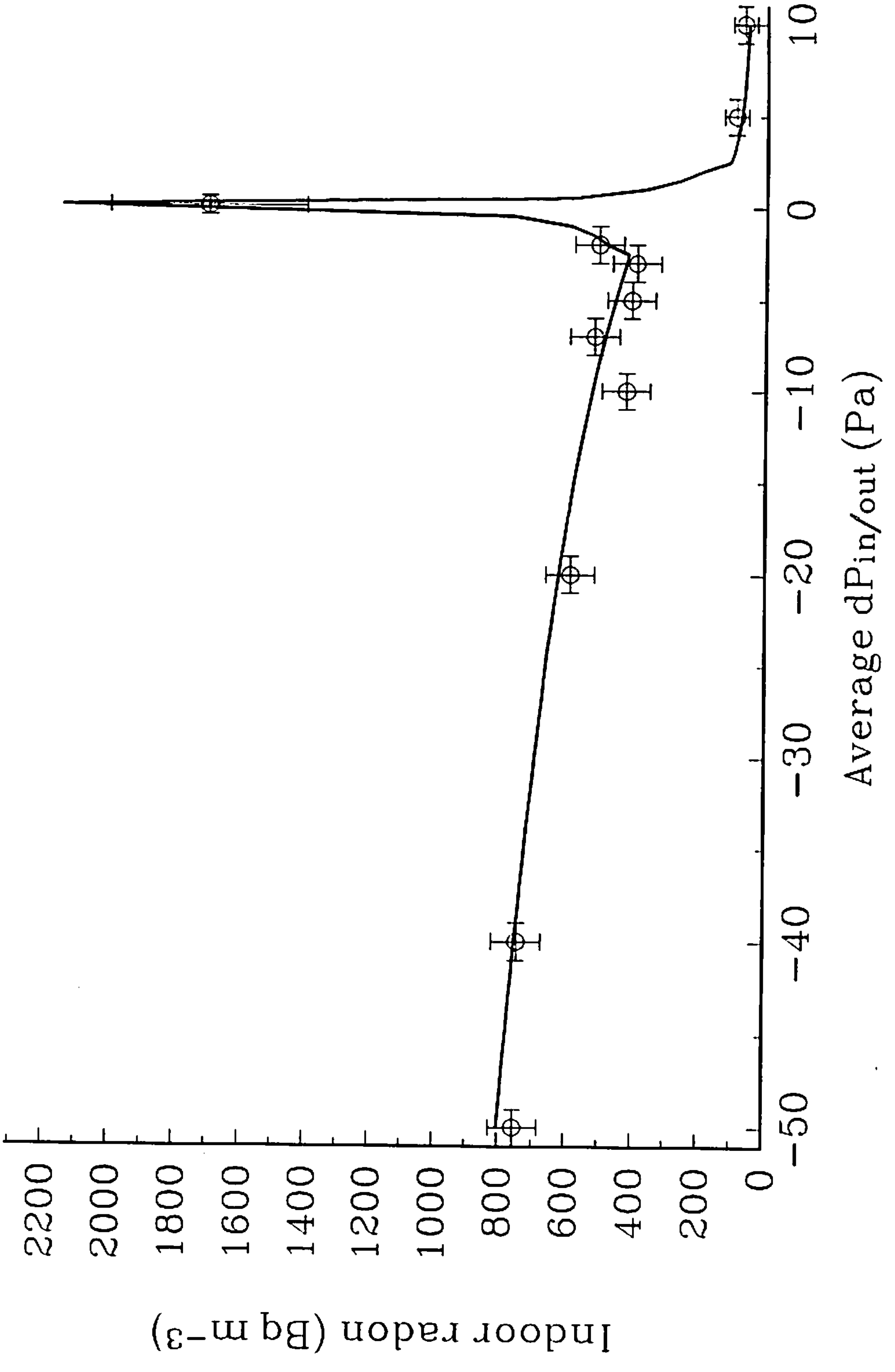


FIGURE 1: INDOOR RADON CONCENTRATIONS AS A FUNCTION OF WHOLE HOUSE PRESSURE CONDITIONS.

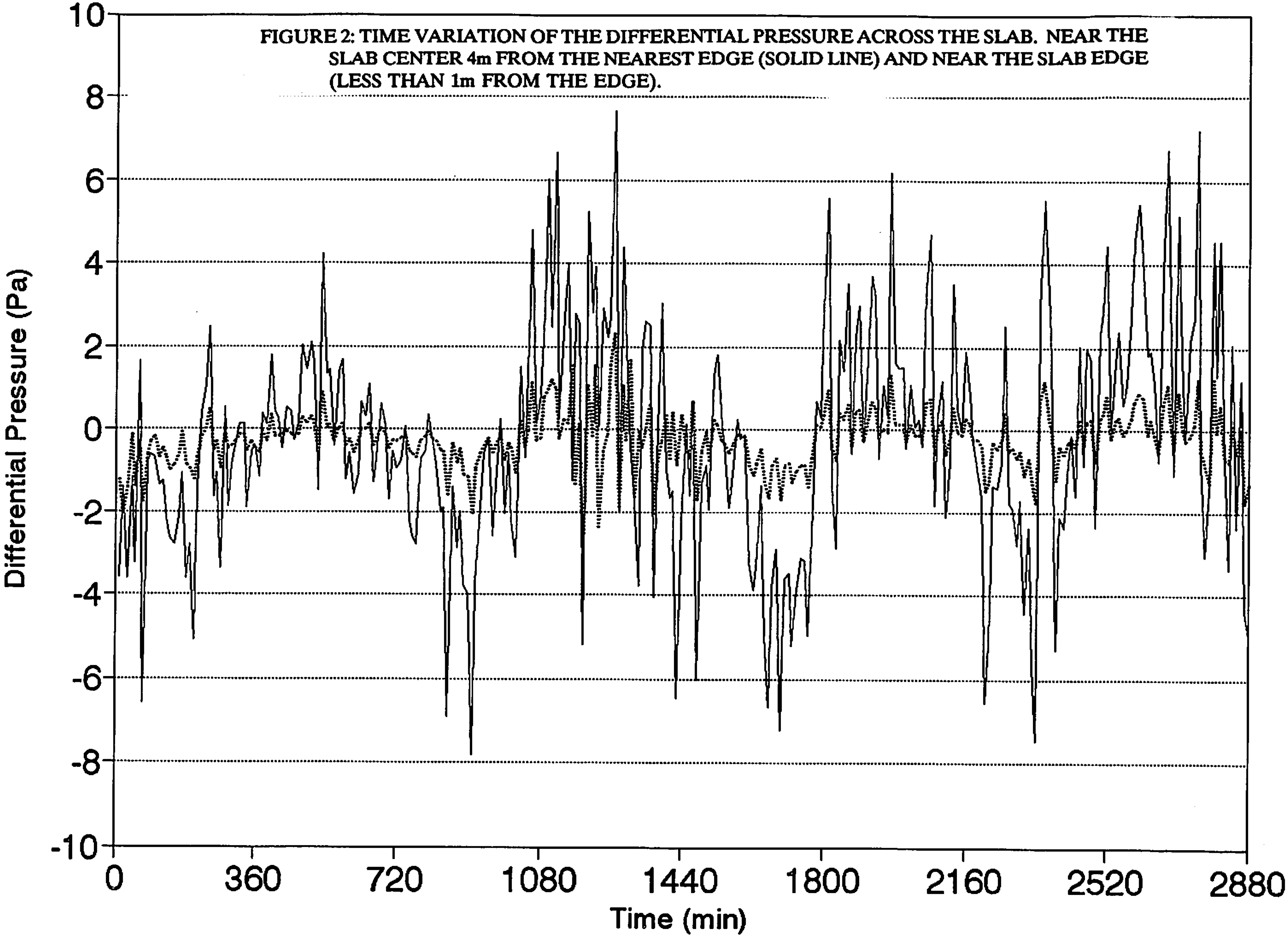
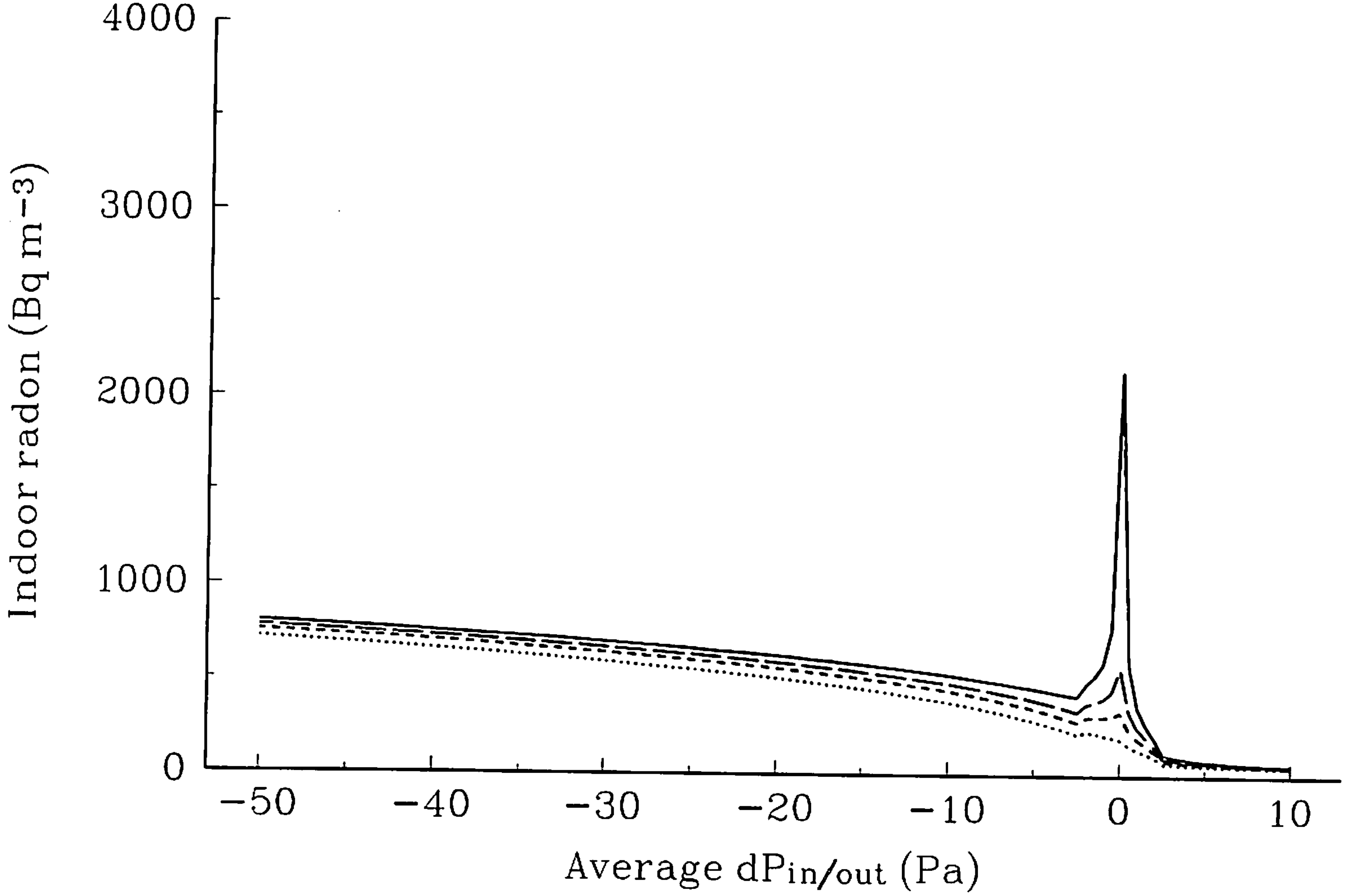


FIGURE 2: TIME VARIATION OF THE DIFFERENTIAL PRESSURE ACROSS THE SLAB. NEAR THE SLAB CENTER 4m FROM THE NEAREST EDGE (SOLID LINE) AND NEAR THE SLAB EDGE (LESS THAN 1m FROM THE EDGE).

FIGURE 3: INDOOR RADON CONCENTRATIONS AS A FUNCTION OF WHOLE HOUSE PRESSURE FOR INCREASED VENTILATION RATES THROUGH CONTROLLED DUCT VENTILATION OF THE HVAC SYSTEM. THE HVAC CONTRIBUTIONS TO TOTAL STRUCTURE AIR CHANGE RATE ILLUSTRATED ARE; 1 ACH (······), 0.5 ACH (----), 0.25 ACH (– –), and 0 ACH (—).



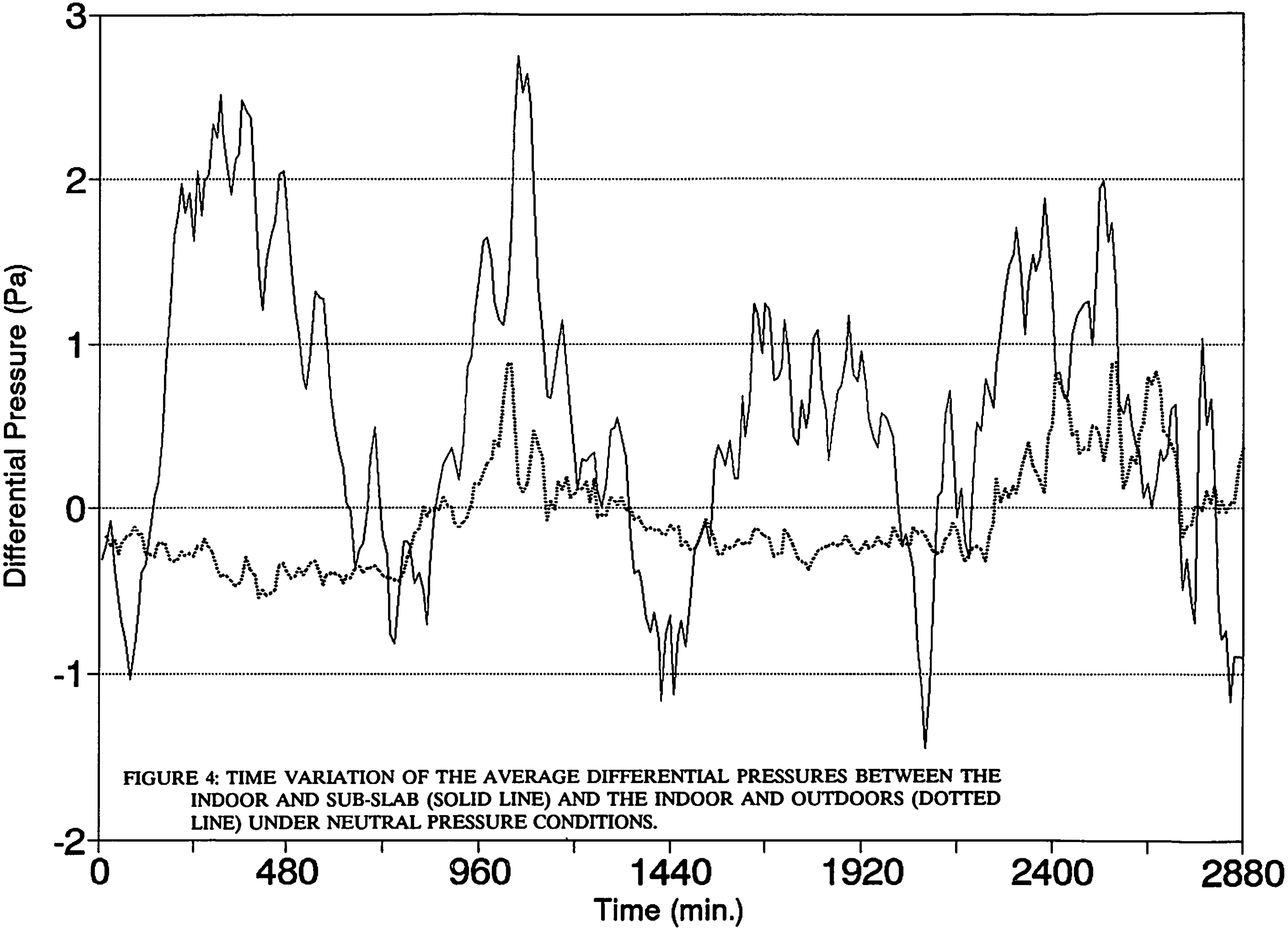


FIGURE 4: TIME VARIATION OF THE AVERAGE DIFFERENTIAL PRESSURES BETWEEN THE INDOOR AND SUB-SLAB (SOLID LINE) AND THE INDOOR AND OUTDOORS (DOTTED LINE) UNDER NEUTRAL PRESSURE CONDITIONS.

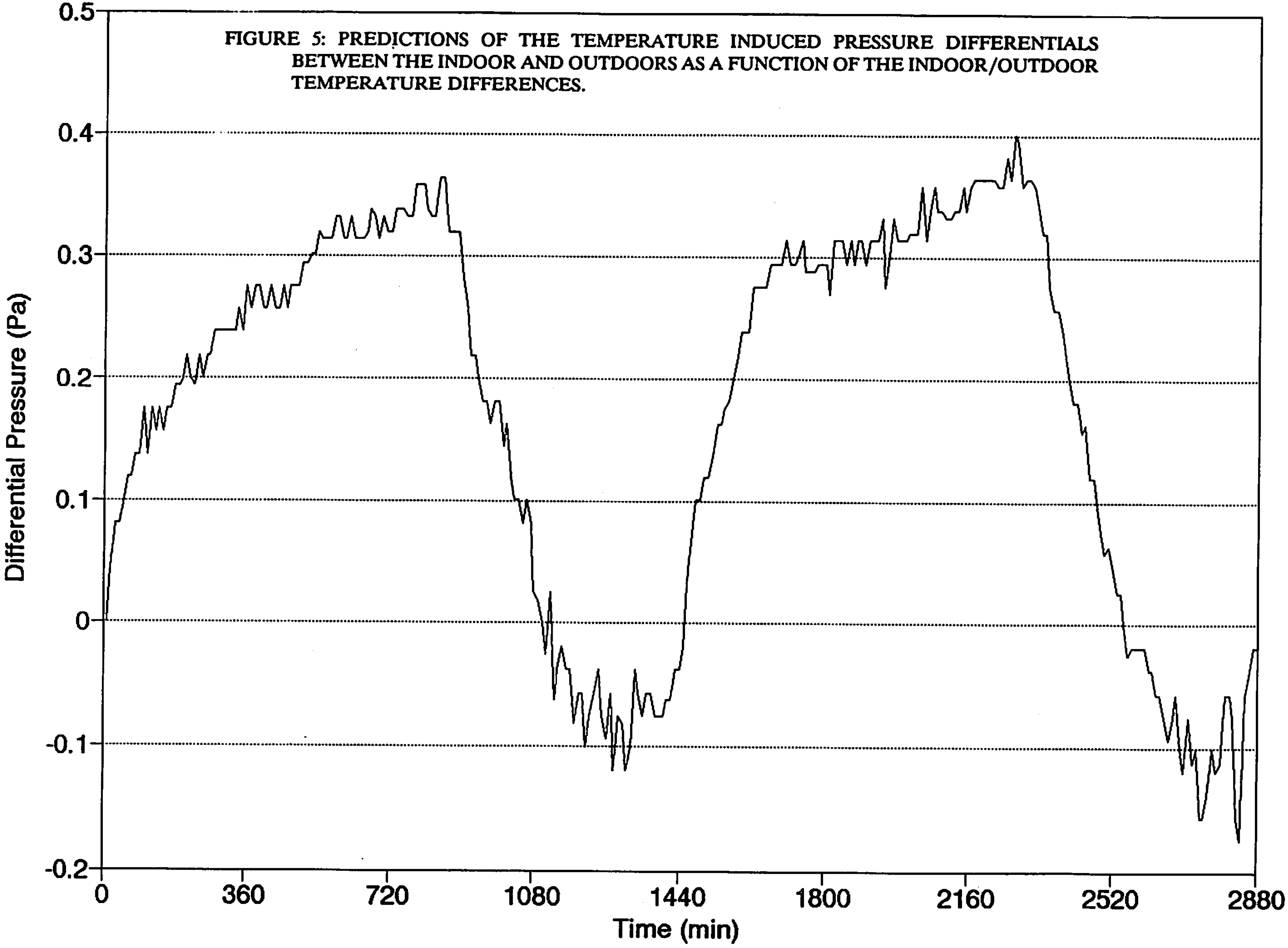


FIGURE 5: PREDICTIONS OF THE TEMPERATURE INDUCED PRESSURE DIFFERENTIALS BETWEEN THE INDOOR AND OUTDOORS AS A FUNCTION OF THE INDOOR/OUTDOOR TEMPERATURE DIFFERENCES.

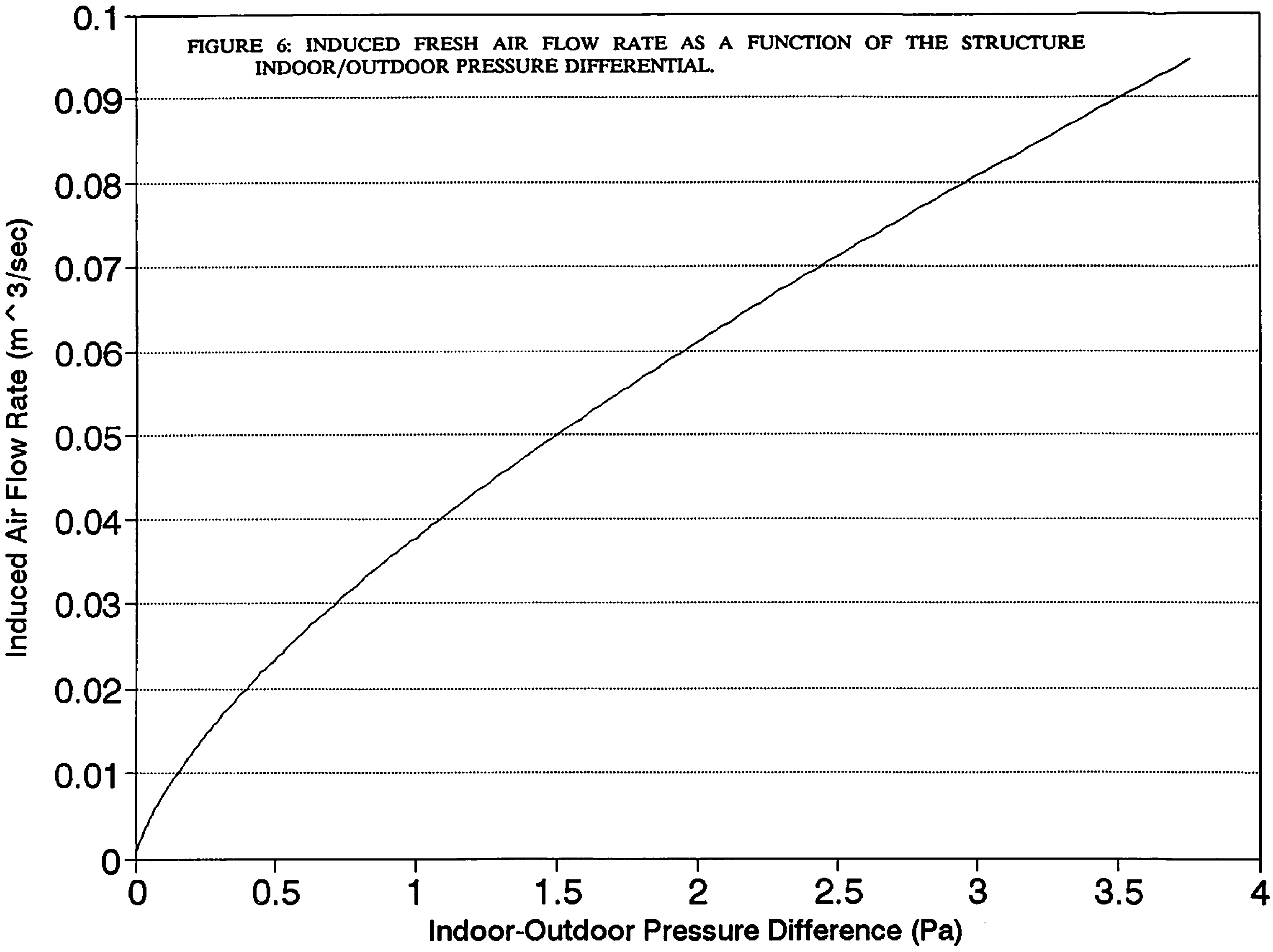


FIGURE 6: INDUCED FRESH AIR FLOW RATE AS A FUNCTION OF THE STRUCTURE INDOOR/OUTDOOR PRESSURE DIFFERENTIAL.

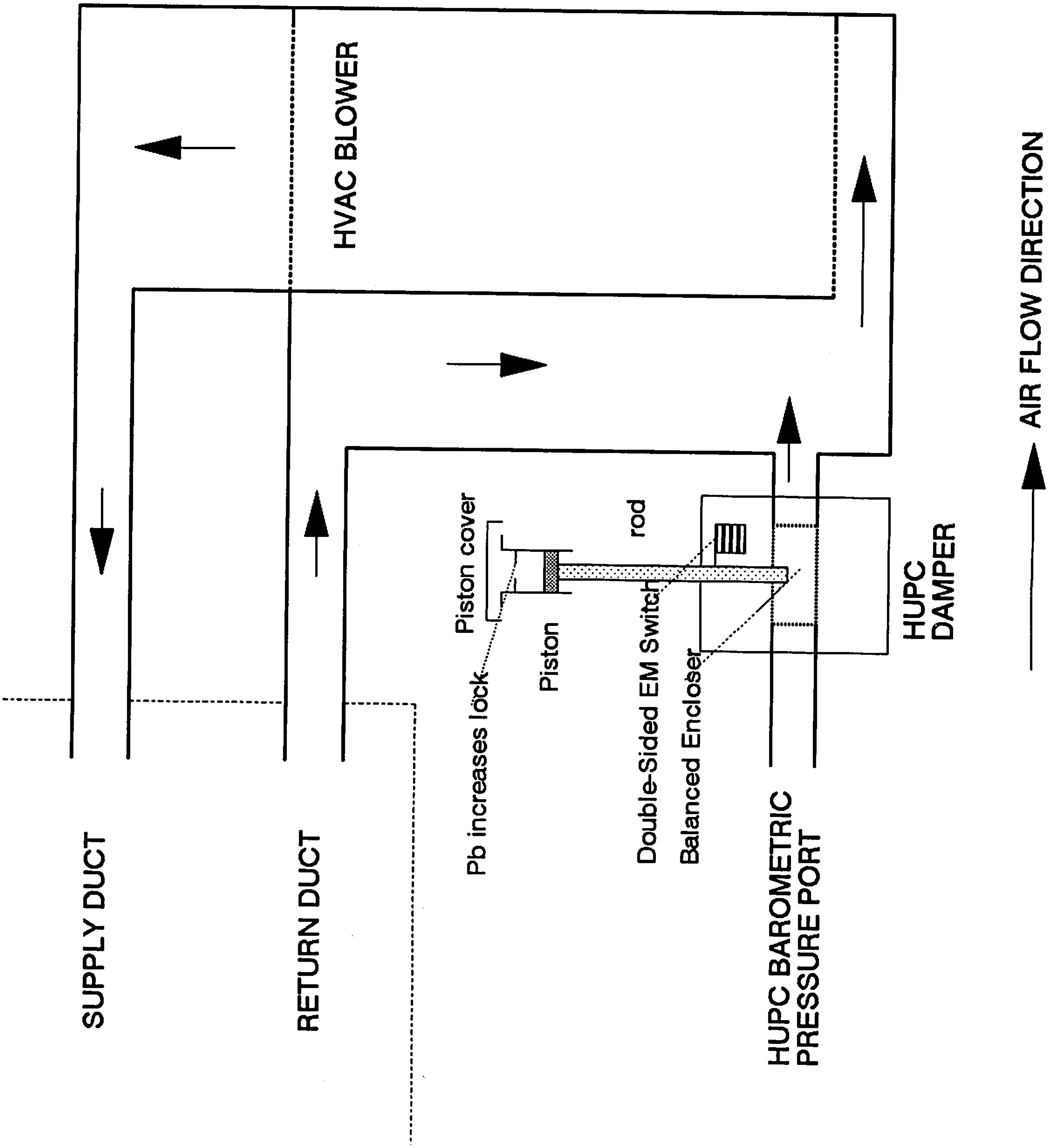


FIGURE 7: A SCHEMATIC DIAGRAM FOR A SIMPLE MECHANICAL APPLICATION OF THE HUPC SYSTEM DESIGN CONCEPT.

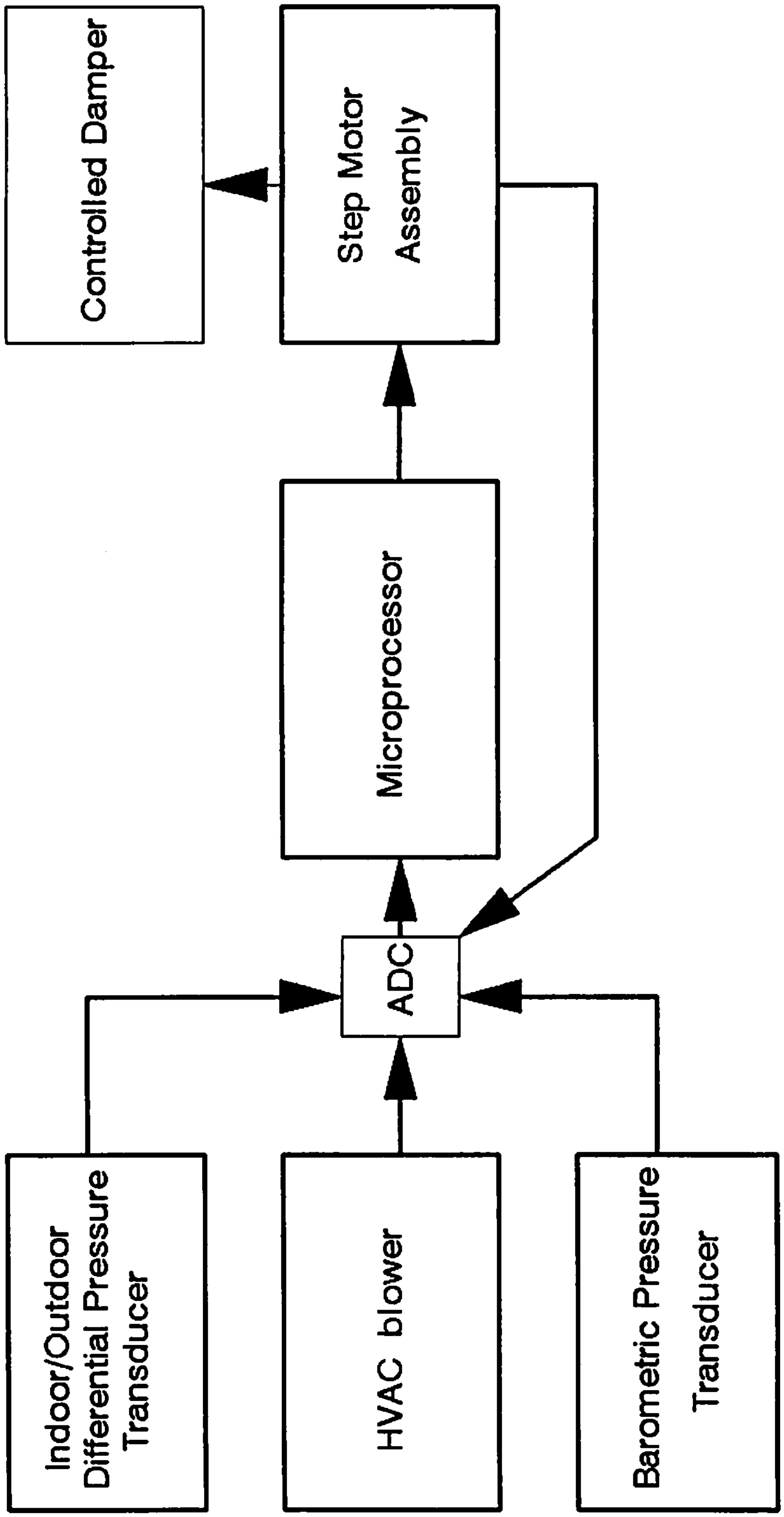


FIGURE 8: A BLOCK DIAGRAM OF A MICROPROCESSOR CONTROLLED HUPC SYSTEM.