DEVELOPMENT OF AN INTERIOR DAMPPROOFING STRATEGY TO PREVENT BASEMENT WALL CONDENSATION DURING CURING

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Summary

On behalf of l'Association Provinciale des Constructeurs d'Habitations du Québec (APCHQ), the Institute for Research in Construction has undertaken an investigation into the cause and potential solutions to the problem of basement wall condensation during the first summer after construction. This project was funded in part by Canada Mortgage and Housing Corporation, through APCHQ.

The research, which builds on fieldwork done by Unies Ltd. for CMHC, involved the implementation of a computer model to test a hypothesis on the mechanisms involved and to evaluate strategies that would defeat the condensation mechanism. The detailed computer simulation tool used was the FSEC model, originally developed by the Florida Solar Energy Center. The model was adapted by IRC to investigate 2-dimensional, dynamic heat and moisture flow in the basement wall, floor slab and surrounding ground.

The investigation involved close collaboration with APCHQ to determine typical construction practice and to characterize case studies of basement condensation problems and attempted solutions.

The simulation results suggest that conditions exist for moisture to accumulate and condense in freshly poured and finished basement walls during warm periods of the year, by way of a vapour-diffusion mechanism which would redistribute the moisture from the concrete to the insulated cavity of the finished wall. As well, building the insulated cavity without building paper between the concrete and the insulation makes this wall particularly susceptible to the vapour diffusion mechanism. Other means to control the mechanism were explored. The results suggest that there may be a better way to assemble a basement wall and operate the house to minimize the risk of this type of condensation.

«Élaboration d'une stratégie de protection contre l'humidité intérieure pour prévenir la condensation sur les murs du sous-sol durant la cure»

Résumé

L'Institut de recherche en construction (IRC) a entrepris, au nom de l'Association provinciale des constructeurs d'habitations du Québec (APCHQ), de rechercher les causes du problème de la condensation se formant sur les murs de sous-sol au cours de leur premier été d'existence, ainsi que des solutions possibles. Cette recherche a été financée en partie par la Société canadienne d'hypothèques et de logement par l'entremise de l'APCHQ.

La recherche, qui s'inspire des travaux que la firme Unies Ltd. a effectués pour le compte de la SCHL, exigeait la mise en application d'un modèle informatique dans le but d'éprouver hypothétiquement les mécanismes en cause et d'évaluer des stratégies visant à contrer la condensation. L'outil de simulation informatique détaillée utilisé était le modèle FSEC, élaboré à l'origine par le Florida Solar Energy Center. Le modèle a été adapté par l'IRC pour étudier le mouvement bidimensionnel dynamique de la chaleur et de l'humidité dans les murs du sous-sol, la dalle de plancher et le sol environnant.

Une étroite collaboration avec l'APCHQ était nécessaire afin de déterminer les méthodes de construction types et de caractériser des études de cas de problèmes de condensation des sous-sols et des solutions tentées.

Les résultats de la simulation indiquent que les conditions sont propices à l'accumulation d'humidité et à la condensation dans les murs de sous-sol fraîchement coulés et aménagés pendant les périodes chaudes de l'année, en raison du mécanisme de diffusion de la vapeur qui transmet l'humidité du béton aux cavités isolées du mur aménagé. De même, ériger la cavité isolée sans intercaler de papier de construction entre le béton et l'isolant rend le mur particulièrement vulnérable au mécanisme de diffusion de la vapeur. D'autres moyens d'éliminer le mécanisme ont été sondés. Les résultats révèlent qu'il peut exister un meilleur moyen d'exécuter un mur de sous-sol et d'exploiter la maison pour réduire le risque de ce genre de condensation.

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Background

In 1987, Unies Ltd. initiated a detailed investigation of basement condensation problems which had been occurring in new Winnipeg houses in summer[1]. That work, undertaken for Canada Mortgage and Housing Corporation, resulted in thorough documentation of 14 case studies which included temperature and relative humidity measurements and sketches of moisture patterns on the concrete after the insulation was removed. Based on the data gathered, Unies postulated that a number of possible factors could make basements prone to condensation and pooling of water:

- cold weather construction followed by summer weather conditions
- full height insulation placed on the interior of the concrete wall
- higher than ambient relative humidity of basement air, combined with concrete surface temperatures at the dew point of that air
- poor air barrier detailing, which would allow moist basement air to circulate in the insulated cavity
- fresh concrete, which would have little or no capacity to absorb and store excess moisture from the air

Unies also concluded that the following factor apparently did not contribute:

- lower concrete wall surface temperatures in the first summer - these were measured to be about the same as those measured in older basements

Remedial measures recommended by Unies included:

- temporarily remove the polyethylene and insulation, exposing the concrete wall to free basement air, and
- ventilate the basement or open windows to provide good drying conditions

Alternative construction practices and preventative measures recommended at the construction stage were:

- insulate the exterior of the concrete,

or

- for interior insulation:
  - leave the wall open for up to a year before insulating
  - take measures to lower interior humidity levels
  - properly seal the air barrier to prevent convective flows from transporting moist air into the cavity

Placing polyethylene or some other vapour retarder between the insulation and the concrete was presumed by Unies not to be a solution since it was felt that condensation would occur on both sides of the membrane; however it was also noted that none of the problem houses had such a membrane.

Since the time of the Unies report, the first-summer basement condensation problem has continued to plague some builders and warrantee programs. Ongoing problems relating to basement condensation have been reported by the Association Provinciale des Constructeurs d'Habitations du Québec, other members of the building community, the energy ministries of Quebec, Ontario and Alberta, and by the general public.

The rash of problems reported to IRC, both directly and through the various agencies mentioned, prompted us to review the Unies work in more detail. We did so to assess whether further research could provide a more complete explanation for the problem, and whether more acceptable and effective solutions could be recommended to the construction community.

Detailed review of the Unies work yielded the following clues to the problem:

1. The sketches of wet concrete surfaces recorded in the Unies report indicated that the residual moisture seemed to persist longer in the corners, which tend to be colder than other foundation surfaces. As well, the regularity of pattern did not suggest air leakage or air convection as a major cause (condensation resulting from air circulation tends to be localized near points of leakage). The sketches suggested that temperature gradients from top to bottom and middle to corner could be involved.

2. The lack of any vapour retarding membrane between the insulation and the concrete in every reported case signaled that excess moisture at the surface of the concrete would be free to circulate through the fibrous insulation and accumulate and condense on an impermeable surface if temperature gradients were present to induce that vapour flow.

IRC subsequently formulated a hypothesis to explain more completely the mechanisms involved, and developed a proposal on behalf of APCHQ for CMHC partial funding to research this issue.

This is the final report of that contract work undertaken with APCHQ for CMHC.

Introduction

The Institute for Research in Construction has undertaken an investigation of the relative performance of various dampproofing strategies for basement walls using advanced computer modelling techniques. The research was executed in two phases:

I - Data Collection
II - Computer Modelling

The results of Phase I were reported in the first progress report[2]; however, data collection continued since the Phase I report. Both phases have been completed and the results are reported below.

Problem Statement

The problem of condensation and pooling of water during the first spring and summer of freshly poured basement walls, insulated on the inside has continued to plague builders in Quebec and elsewhere, in spite of solutions proposed by the research community. It is felt that the solutions offered have not been fully proven and have been viewed as restrictive or impractical by builders. A broader range of effective and inexpensive solutions are needed to address the problem.

Review of literature and of recent cases of basement condensation has suggested a new hypothesis for the cause of the problem - a hypothesis that could be tested by systematic investigation of the combined heat, air and moisture transfer in the basement wall using advanced computer simulation techniques.

The Hypothesis

It is hypothesized that a two-dimensional vapour diffusion mechanism is contributing strongly to the basement condensation problem in the first spring and summer, by redistributing excess water in the concrete through the interior insulation to the vapour barrier surface and to the bottom of the concrete wall, as a result of inward and downward temperature gradients in the saturated wall in spring and summer. This mechanism would take place in an unimpeded fashion, in the absence of any form of vapour diffusion retarder at the surface of the concrete.

Objective and Scope

The objective is to confirm that the mechanism of vapour diffusion induced by inward and downward temperature gradients in the wall in summer is the major factor involved in the problem, and to identify effective and inexpensive strategies to control or prevent excessive build-up and pooling of water.

The scope of this project is to investigate, using computer simulation, several strategies that would be acceptable to builders and would minimize the risk and extent of damage caused by the condensation problem.

Phase I - Data Collection

Data Collection

The data collection consisted of a review of current construction practice and case studies of reported basement condensation problems.

Current Construction Practice

Review of basement construction practices and case studies with APCHQ[3] and Canadian Portland Cement Association[4] has provided the following information.

Typical basement construction consists of a full depth basement with 200 mm (8") concrete wall, insulated on the interior to either 600 mm (2 ft) below grade or to the slab (full depth). The concrete typically has a water-cement ratio of 0.6 at pouring. This quickly drops to 0.5 after pouring due to spillage and drainage through the form work, and eventually to 0.3 to 0.4 when fully cured. The difference between the water-cement ratio of 0.5 after pouring and ratio when fully cured is attributed to evaporative drying - the phenomenon which is believed to be the source of the problem. Cured concrete strengths are of the order of 15 - 20 MPa. The density of the finished and cured concrete ranges between 2000-2400 kg/m^3.

Basement wall insulation is either rigid or an assembly consisting of an RSI 2.1 (R12) batt placed in the cavity formed by 38 x 64 mm studs (2x3 studs) @ 400 mm (16") on center. The studs are installed 25 mm (1") out from the wall to accommodate the thicker batt. A dampproofing coating is applied onto the exterior face of the concrete, from grade down. Building paper can be used on the interior face of the concrete from grade to slab but can be omitted when wood framing is not used or when the framing members are not in direct contact with the concrete. Polyethylene is used as the vapour barrier applied to the inner face of the studs and batts. The interior walls are finished with gypsum board.

Typical Scheduling

- forms are removed within 24 hours after pouring of the concrete
- exterior dampproofing and backfilling can occur within 5 days of pouring
- interior framing, insulating and finishing can occur within 45 days

Pouring the concrete wall in March or April can result in the basement wall being closed-in and finished in May or June. In June and July of the first year, excess water and moisture in the concrete is subjected to higher temperatures outside and near the top of the wall due to solar effects and warm ambient temperatures. Temperatures at the interior of the wall and at the bottom of the wall are lower as the ground is still cool from winter and basement air is typically unheated during this period.

Confounding Factors

Three confounding factors were identified by APCHQ:

1. Some regions of Quebec feature sandy soils with high water tables. This occurs typically in the foothills of the Laurentians; e.g., the Joliette region. General basement condensation problems have been reported and investigated by APCHQ in this region. Slab temperatures have been measured at 3°C in July. APCHQ recommends covering slabs with extruded polystyrene to avoid slab condensation in these locations.

2. Studs used for framing are often 'green' at the time of construction. When the basement walls are closed-in, the moisture in the near-saturated studs can only escape to the adjacent cavity - which is bounded by moist concrete on one side and polyethylene on the other. There is no obvious route for any of the excess moisture to escape during this period, except by condensation on the coldest surfaces and subsequent drainage.

3. As is typical of indoor conditions at completion of construction, the indoor relative humidity tends to be high - as pointed out by Unies. This condition represents yet another potential source of moisture, or at least the absence of a drying influence.

Field Trials of Control Strategies

A number of solutions that would prevent the moisture on the concrete surfaces from condensing in the cavity had been postulated over the course of the project. APCHQ took the initiative to have some tried, while others emerged from the building community:

1. A dampproofing coating was applied to the inside surface of the concrete to "seal" the moisture in. It was found that the still wet concrete apparently prevents a good and continuous bond between the dampproofing and the concrete, defeating the intended seal.

2. Builders in the region of Québec city have applied extruded polystyrene directly to the inner face of the concrete, immediately after the formwork is removed and before the slab is poured. The insulation is applied to the wall, down to the footing. The slab is subsequently poured so that the outer edge of the slab is formed against the insulation. Should moisture present itself at the concrete/insulation interface, it would presumably drain to the footings and underneath the slab. No problems have been reported with this innovative approach.

3. In one instance, homeowners reporting the condensation problem to APCHQ in the summer of 1993 were advised to turn the thermostat controlling the baseboard heaters in the basement up to 21°C - this apparently had little effect. They were subsequently instructed to set the thermostat to 25°C, at which setting, evidence of condensation disappeared within a few days.

Example Cases Reported to IRC

Of the several cases reported directly to IRC, three did not fit the usual description of the problem and are worth noting:

1. Severe condensation problems were reported in summer for a "roll bag" installation, where the insulation was applied to only 600 mm (2 ft) below grade. There was no building paper, nor polyethylene separating the batt and the fresh concrete. The most seriously affected wall was south facing, which had no shading from the sun. On one warm sunny day, the surface temperature of the concrete wall exposed to the sun was measured to be 27°C, whereas the inner surface of the concrete was at 20°C. Residual moisture which had condensed on the polyethylene over the summer was observed as late as mid-September. Before this case was recorded, it had been previously thought that the full height application of insulation and vapour barrier was somehow a cause of the problem.

2. New homeowners that had already gone through an episode of basement condensation with a previous house, instructed the builder not to close-in the basement wall in their new house for 3 months. This was done, but two weeks after closing-in the wall in July, extensive condensation occurred on the polyethylene. Apparently, relying on drying time alone may not be enough to avoid the problem.

3. In another case, severe condensation problems were reported in spring shortly after the basement wall was retrofitted with full height insulation, installed on a 30 year old concrete block basement wall. The concrete blocks had previously been sealed and painted with a vapour barrier paint. The source of the moisture was postulated to be the green lumber used, although this could not be verified. Once released to the cavities, the moisture apparently condensed on all cool, low permeability surfaces and pooled at the bottom. This case highlights that although the excess moisture in curing concrete is suspected to be the main source of moisture in most cases, the moisture in green lumber is also a likely contributing source.

The information gathered in Phase I was used to define the configuration and simulation conditions needed to model the phenomenon. A general conclusion that emerges from Phase I is that a diversity of conditions appear to be involved in the summer condensation problems, and singling out or ruling out contributing factors could not be done by simply reviewing case studies. Consequently, the modelling would have to be as detailed as possible for the second phase of investigation. The modelling effort was reported in Phase II.

Phase II - Computer Modelling

Model Selection and Adaptation

A number of candidate models were reviewed for the task, including:

- the "Transient Coupled Convection and Conduction 2-Dimensional" model (TCCC2D) developed by VTT-Finland
- a detailed and more comprehensive model currently under development at IRC (LATENITE),
- a generalized solver of multi-dimensional, heat, air and moisture flow problems developed at the Florida Solar Energy Center (FSEC).

After detailed review of all model capabilities, it was determined that the FSEC model was most suited for adaptation to our research project. Appendix A outlines the reasoning behind this decision.

Model Attributes

The **FSEC** model is a 3-dimensional general purpose software package specifically designed to simulate complex building science problems. The program offers unique features, including an ability to solve user-defined systems of governing equations. Up to 250 coupled differential equations and their boundary conditions may be either selected from libraries or defined by the user. The use of finite elements allows the model to accommodate very complex structures and geometries, which is a very important feature in the basement condensation project.

Moisture Transport and Storage
The moisture transport modules use the *evaporation and condensation theory,* assuming:

- moisture travels due to water vapour density gradients; i.e. due to differences in the partial pressure of water vapour
- local thermodynamic equilibrium exists
- the total pressure is constant, and
- the solid matrix is rigid.

In a control volume (element), the net amount of water increase in the pores is equal to the amount of water vapour brought to the pore by diffusion minus the amount of liquid water accumulated. Because at all times thermodynamic equilibrium prevails, the amount of liquid water at any given point can be calculated through the equilibrium sorption isotherm with knowledge of temperature and water vapour density at that point.

Heat Transport and Storage
Additionally, the net amount of energy stored in the same control volume is equal to the amount of heat conducted plus the energy liberated during the phase change.

Air Flow *(not modelled)*
For the purposes of this first simulation of this phenomenon, the effects of air flow and circulation through the basement wall system were not modeled. It was felt that, for the sake of simplifying an already complex model, and the fact that air flow was not needed to test the vapour-diffusion hypothesis, air flow could be left for future investigation, should the vapour-diffusion explanation prove not to be the apparent mode of vapour transport.

The **FSEC** model has been applied to several moisture problems and good agreement has been found with analytical solutions[7,8].

Appendix A includes more detail of the model and material properties used in the simulation.

Implementation

The main elements of the 2-dimensional model of the basement are depicted in Figure 1. Several of the elements shown in this picture were varied in the analysis, such as the depth of the water table (4.28 and 8.28 meters), and the basement temperature (15 & 25°C). As well some of the moisture controlling elements were removed to see the effect; e.g., the building paper and the polyethylene.

Several simplifications had to be made to keep the complexity of the model to a workable level:

- wood studs were not included in the model, as this would require a three dimensional analysis. Based on some of the anecdotal evidence cited above, the initial moisture content of the wood studs could have a major impact on the moisture balance in the cavity. The impact of the initial moisture content of the studs has been left for future investigation. Nevertheless, the roll-bag example, which featured no wood studs, is evidence that the summer condensation problem can occur without wood studs.

- the concrete of the basement wall and slab was assumed to be uniformly just below saturation when the wall is closed-in and when the simulation begins. Current limitations in modelling prevent us from initiating the simulation with super-saturated concrete.

The boundaries of the heat and moisture flow system are shown in Figure 2. The key boundaries are the ground surface and the top portion of the concrete wall which are exposed to weather. For this study, hour-by-hour weather for Montreal[9] was used. The weather data included ambient air temperature, relative humidity, and incident solar radiation. Physical properties of materials used in the simulation are recorded in Appendix A.

Description of the Simulations

In total, eleven simulations were performed with varying conditions to explore the sensitivity of condensation potential to different basement wall characteristics and boundary conditions. The cases and conditions are listed in the table below.

Case	Start date / Hours of Simulation	Basement Temp.	Basement RH (approx.)	Depth of Water Table	South Solar Gains?	Membrane Between Insul. & Con.	Vapour Barrier
A1	April 6 / 8760	15°C	60%	4.28	yes	none	none
A2	April 6 / 8760	15°C	60%	4.28	yes	bldg pap.	bldg pap.
B1	May 1 /1200	15°C	60%	4.28	no	bldg pap.	poly
B2	May 1 / 1200	15°C	60%	4.28	yes	bldg pap.	poly
B3	May 1 / 1060	15°C	60%	4.28	yes	none	poly
B4	May 1 / 1200	25°C	33%*	4.28	yes	none	poly
B5	May 1 / 1200	15°C	60%	4.28	yes	bldg pap.	bldg pap.
C1	May 1 / 1000	15°C	60%	8.28	yes	none	none
C2	May 1 / 1000	15°C	60%	8.28	yes	bldg pap.	poly
C3	May 1 / 1000	25°C	33%*	8.28	yes	none	none
C4	May 1 / 1000	15°C	60%	8.28	yes	bldg pap.	poly

* 33% RH @ 25°C represents the same absolute humidity (and vapour pressure) as 60% @ 15°C

For 9 simulations, it was assumed that the basement wall was closed-in on May 1. For two simulations, the walls were closed-in on April 6, with the initial and boundary conditions described above. Most simulations were run for approximately 1200 simulated hours - about 50 days to study emerging trends. Two simulations, A1 & A2, involved a full year.

For each case, all temperatures and moisture contents were calculated by the model at every point of the finite element grid shown in Figure 3a. Data for selected locations at the top, middle and bottom of the wall shown in Figure 3b was recorded on file every four simulated hours:

- temperature of the insulation at the inner face, next to the polyethylene
- relative humidity of the air in the insulation at the inner face, next to the polyethylene

As well, average temperatures and water contents the following components were recorded:

- the above-grade portion of the concrete wall
- the below-grade portion of the concrete wall
- the concrete slab
- the building paper (if present)
- the insulation layer

Confirmation of the Hypothesis with the Model

Case B3 includes characteristics and conditions that are hypothesized to lead to condensation problems in the wall: the above-grade concrete is exposed to warm spring-time conditions, including strong solar radiation on sunny days; as well, the basement wall has no building paper separating the concrete and insulation from grade down and includes the polyethylene vapour barrier on the inside surface of the insulation. Figure 4 shows the predicted relative humidity of the air at a vertical plane in the insulation, 35 mm inside the polyethylene. As can be seen, the relative humidity in the insulation fluctuates widely at the top of the insulation, momentarily reaching 100% towards the end of the simulation. The RH at mid-height and bottom of the insulation tends more steadily towards 100% throughout the simulation period. The point of steady condensation (RH > 100%) is reached at mid-height after 1000 hours from the start date of May 1. The bottom part of the wall appears to be heading towards the saturated condition as well. This indicates that the conditions exist in this wall for moisture to accumulate into condensation at about the second week in June. (Note: the simulation ends at this point because the model becomes unstable when elements reach saturation).

Figure 5 shows the corresponding temperature profiles at the same vertical plane within the insulation. The wall warms progressively through this period, responding to exterior weather patterns. The temperatures at the top part of the wall fluctuate due to weather, whereas the mid and bottom parts of the wall lag in temperature due to the mass effect of the earth. Since the temperature of the basement air is cooler at 15°C, temperature gradients in the insulation are, for the most part, inward to the basement and downward to the bottom of the insulation - as hypothesized. The periods of rapid rise in relative humidity of the air in the insulation correspond to periods where the above-grade portion of the basement wall is exposed to warming influences from outdoors. It should be noted that RH is only an indirect indication of the amount of moisture in the cavity air. However, in these simulations, the RH of the cavity air increases with warmer temperatures, suggesting that the absolute moisture increases considerably as well. (If the absolute humidity of the cavity air had remained constant, the RH would have dropped with higher temperatures).

These modelling results suggest that the hypothesis is correct: vapour diffusion, driven by inward and downward temperature gradients in the basement wall, can cause condensation in the insulation for Montreal weather conditions that prevail as early as the second week in June, given a close-in date of May 1.

Analysis of Other Results

Four other simulations were undertaken to evaluate the potential for moisture accumulation in the basement wall cavity for different wall constructions and different boundary conditions, over the same time period. These variations in constructions and conditions are listed in the above table for the series of simulations labeled "B".

The total amount of moisture in the insulation was plotted over this period, as shown in Figure 6. The case used to test the hypothesis (case B3 with solar gains on the above-grade wall, no building paper) shows a much more rapid increase in the total amount of moisture in the insulation over this period than any other case tested. All other cases have at least one feature that works against the mechanism:

Case	Strategy
B1	- addition of building paper, shaded from solar gains
B2	- addition of building paper
B4	- setting the basement temperature to 25°C
B5	- addition of building paper and substituting building paper for polyethylene

Relative to case B3, the other strategies appear to have a similar effect; however, there are differences. These are highlighted in Figure 7, which repeats the information in Figure 6 without case B3, and features a narrower scale. Although the strategy of keeping elevated basement temperatures (B4) results in a reduced moisture load compared to case B3, this case appears to be more susceptible to warmer exterior temperatures than the other measures. This measure works by keeping the insulation and polyethylene above the dewpoint of the cavity air, which is not as easily achieved in warmer weather. Cases B1 and B2, both with building paper added, perform even better throughout the simulation period, suggesting that vapour diffusion control could be the most effective solution to the problem. Shading the exposed wall from solar radiation (B1) appears to have some advantage over leaving it exposed to solar gains; however, as can be seen with the merging graphs, the advantage is short-lived. This suggests that as the weather warms, differences between shaded and unshaded walls may not be significant.

Balancing the permeability of the two sides of the cavity with building paper (B5) results in a steadier moisture content in the insulation that eventually falls below those resulting from other strategies. This suggests that a very low permeability vapour barrier may not be the ideal material for moisture protection in basement walls.

Full year simulations were performed to further investigate the effect of reducing the vapour resistance of the vapour barrier and eliminating it. The simulation period was extended to a full year to investigate whether the emerging solutions for summer condensation would increase the probability of winter condensation. Case A1 was run to show that removing the air barrier as well as the building paper promotes fast spring and summer drying; however, as would be expected, the outer layers of insulation at the top of the wall do become saturated in the next winter. This is shown in Figure 8. This graph also suggests that delaying the placement of the vapour barrier to late summer or early fall could help address both condensation seasons. Figure 9 shows corresponding temperatures over the same period. It can be seen that temperature gradients start reversing (from downward to upward) at about 4500 hours after April 6, which corresponds to mid-October. At this point, we would expect all signs of the phenomenon to have disappeared, even if residual moisture remained in the wall, because that moisture would be driven upward and outward.

Case A2, which is a full year run of case B5 (building paper on both sides), was performed to assess whether the greater overall permeability of this wall system, which assists the cavity in the summer, does not result in saturated conditions in the outer part of the insulation in the next winter. The results are reported in Figure 10. These suggest that the relative humidity in the cavity fluctuates within a relatively narrow band with changing season and does not reach saturation in winter.

Cases C1 to C4 were simulated to investigate the sensitivity to the assumption on the depth of water table. Case B2 and C2, which are identical cases except for the water table depth, showed virtually identical moisture movement patterns. It is postulated that much shallower water table depths would be required before a significant impact on moisture movement would be noticed. This is left to future investigation. Case C3 - a repeat of C1 with 25°C basement temperature - was simulated to find out whether the wall, initially left to dry without polyethylene or building paper, could be made to dry even faster by raising the basement temperature. It was found that raising the basement temperature had little additional effect on the rate of drying of the concrete in the wall. Raising the temperature did result in faster drying of the slab, which is not necessarily desirable result.

Discussion

The following principle emerges from this detailed analytical work:

In an enclosed cavity that has saturated materials in contact with the cavity air; i.e. in contact with the air in the insulation, the dew point of the cavity air tends to be the same as the temperature of the warmest saturated material. If the saturated material (the concrete) reaches 20°C for example, then the dew point of the air in that cavity becomes 20°C as the air comes into vapour equilibrium with the material. Any other impermeable member exposed to the cavity that is less than 20°C; e.g., the polyethylene in contact with 15 °C basement air, or the lower part of the concrete wall in contact with the cold ground, will be susceptible to accumulate moisture, as long as the saturated material remains saturated at the higher temperature.

The presence of the building paper below grade apparently offers enough resistance to vapour flow into the cavity that the air in the cavity doesn't have a chance to come into vapour equilibrium with the warmer, saturated concrete. The concrete dries out and/or the temperature gradients in the wall change with the season before the cavity vapour pressure has a chance to fully respond. As well, the fact that the building paper is apparently effective even without being placed above grade suggests that the above-grade concrete dries outward during cooler weather and is not contributing greatly to the cavity moisture load. Rapid drying of the above-grade portion of the concrete was observed in the simulations.

Finally, with building paper placed instead of the polyethylene, the cavity air is able to rid itself of additional moisture during the warm periods, reaching some equilibrium that is well below saturation.

Conclusions

Keeping in mind that two important modelling simplifications were made - no air flow was modeled and the modeled cavity had no wood studs - and keeping in mind that modeling can only give direction to what should be confirmed by testing, the following conclusions have emerged from this investigation:

The evidence accumulated through simulations suggests that the hypothesis is correct: the vapour-diffusion mechanism driven by inward and downward temperature gradients is likely a major contributing factor resulting in the increased incidence of summer condensation in newly built basements.

The case studies suggest that many interrelated factors can contribute to the mechanism but not all need to be present for the problem to occur. Preventative measures to defeat the mechanism at the construction stage should be considered by builders who run a higher risk of occurrence of first-summer condensation. Based on evidence of case studies and of the modelling, these high risk factors would be:

- spring or early summer construction that features rapid finishing of the basement wall on the inside, and with permeable insulation installed without building paper separating the insulation and the concrete below grade

- the above conditions in high water table areas that keeps the foundation surfaces exceptionally cool, or
- the above conditions in a site where a significant portion of the basement wall is exposed to warm summer air and sunlight, causing the concrete to become warmer than the basement air; e.g. units with final landscaping delayed leaving more of the wall exposed over the first summer period.

Recommendations

Many of the recommendations made by Unies listed in the Background section of this report remain valid; however, a redirection in emphasis may be warranted. Specifically, including the building paper between the insulation and concrete from grade to floor (as is required when wood framing is applied to the concrete) may provide additional condensation resistance where other measures are failing.

As well, the notion that going to full height insulation is to be blamed for the increase in occurrence of the problem is probably not the correct explanation in itself, since we have direct evidence of the phenomenon occurring with part-height insulation. A more likely explanation is that a part-height frame for the cavity insulation is almost always fastened to the concrete wall, and therefore requires the building paper. A full-height frame can be fixed to the slab and therefore need not be fastened directly to the wall for support, thereby eliminating the code-related need for building paper. The shift to full height insulation has presumably resulted in a shift away from using the building paper. This is the more likely cause of the increased occurrence of the problem with full height installations in the last ten years.

Based on the simulation results and case studies reported, the following alternatives to summer condensation prevention appear to be promising; however, these should be tested either in the lab or in field experiments before a general recommendation is made:

- vapour diffusion control:
  - bring back the building paper, if it has been omitted from current practice,
  - as done by some Quebec builders, consider installing an inside layer of extruded polystyrene (which is relatively impermeable) down to the footing, before the slab is cast, thereby providing a drainage path for moisture condensing at the interface (this also isolates the cold concrete wall surfaces from potentially moist interior air)
- temperature control in the first summer: keep the polyethylene and insulation from falling below the dewpoint of the cavity air by heating the wall from inside, not from the outside:
  - find some means of keeping the exposed portion of the concrete cool during warm weather, perhaps using the same materials used to keep the concrete warm during cold weather construction
  - instruct homeowners to ensure that the basement doesn't go cold during warm spells in the first summer: heat the basement directly if zone control is possible; e.g. with baseboard heaters on a local thermostat (note that rapid drying of the slab was observed for the simulations with the basement temperature at 25°C ; this measure could result in uneven hydration of the slab, a condition linked to cracking and curling)
- eliminate the sources of moisture before closing in:
  - allow the concrete to dry as long as possible. If completion is in May or June, and concrete is still fresh, set up studs and insulation but not the polyethylene until after the July/August warm spell (this may be problematic for final inspection and closing the contract with the new owner).
- counteract all of the mechanisms with exterior insulation (as identified by Unies):
  - this generally reduced the temperature gradients in the concrete
  - it promotes heating of the concrete from the inside, thereby setting up outward temperature gradients and moisture flow

- it generally results in warmer concrete surfaces, thereby getting these above dew point temperatures of the room air
- it allows any moisture that does flow inward to do so freely without being trapped on impermeable surfaces.

Finally, more systematic investigation of the balance between the permeability of moisture controlling membranes on the interior and exterior of the cavity could yield combinations that minimize the probability of both summer and winter condensation. IRC's adaptation of the FSEC model offers a unique opportunity to engineer the moisture controlling features of the basement wall.

References

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2. Development of Interior Dampproofing Strategy to Prevent Basement Wall Condensation - Phase I. IRC contract report to APCHQ and CMHC, February, 1993

3. André Gagné, Chef d'équipe, Soutien Techniques, Association Provinciale des Constructeurs d'Habitations du Québec. Personal communication, October 8, 1992.

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5. Catalogue of Material Properties. International Energy Agency - Annex XIV: Condensation and Energy, Volume 3, March 1991.

6. Florida Solar Energy Center (FSEC) Model - Properties Database.

7. Kerestecioglu, A., M. Swami, R. Dabir, N. Razzeq and P. Fairey. "Theoretical and Computational Investigation of Algorithms for Simultaneous Heat and Moisture Transport in Buildings" FSEC-CR-191-88, Florida Solar Energy Center, Cape Canaveral, 1988.

8. Kerestecioglu, A., L. Gu "Theoretical and Computational Investigation of Simultaneous Heat and Moisture Transport in Buildings: Evaporation and Condensation Theory". Presented at 1990 ASHRAE Winter Meeting, Atlanta, GA, Feb. 11-14, 1990.

9. "Picked Meteorological Year Weather File: Montreal Dec. 70 - Nov. 71. Weather tapes created for NRC by Atmospheric Environment Service.

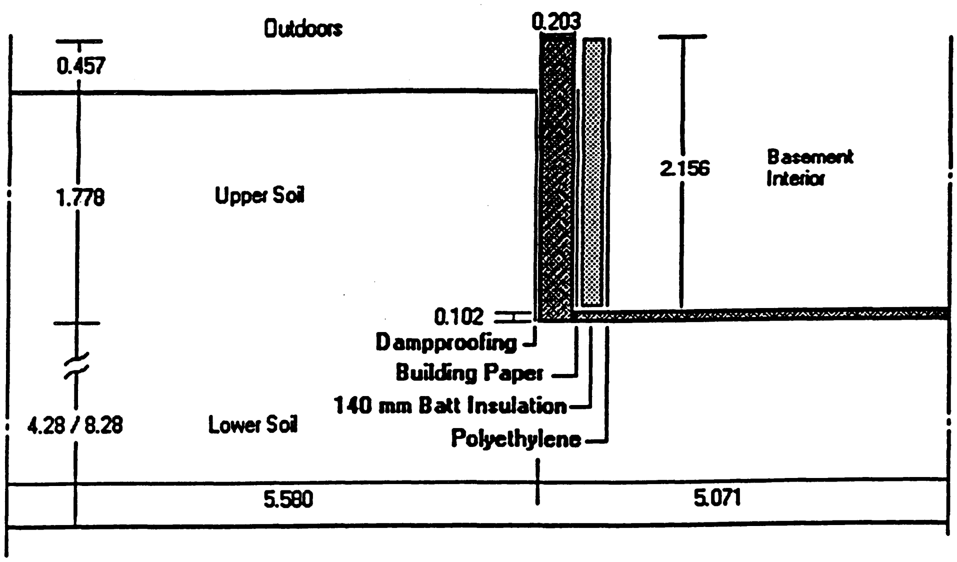

Figure 1. Basement Cross Section
(Dimensions in meters. Not to scale)

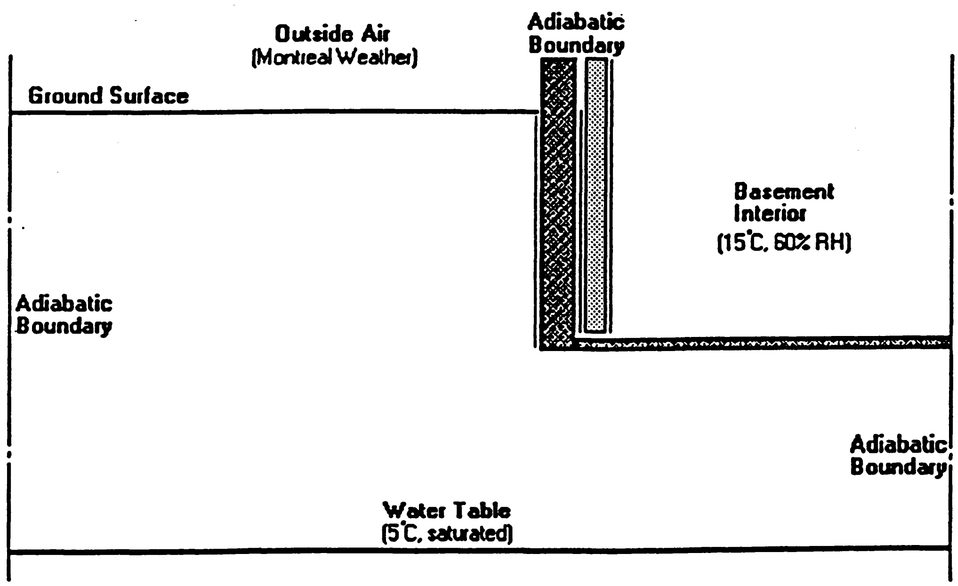

Figure 2. Boundaries of the Heat & Moisture Flow System

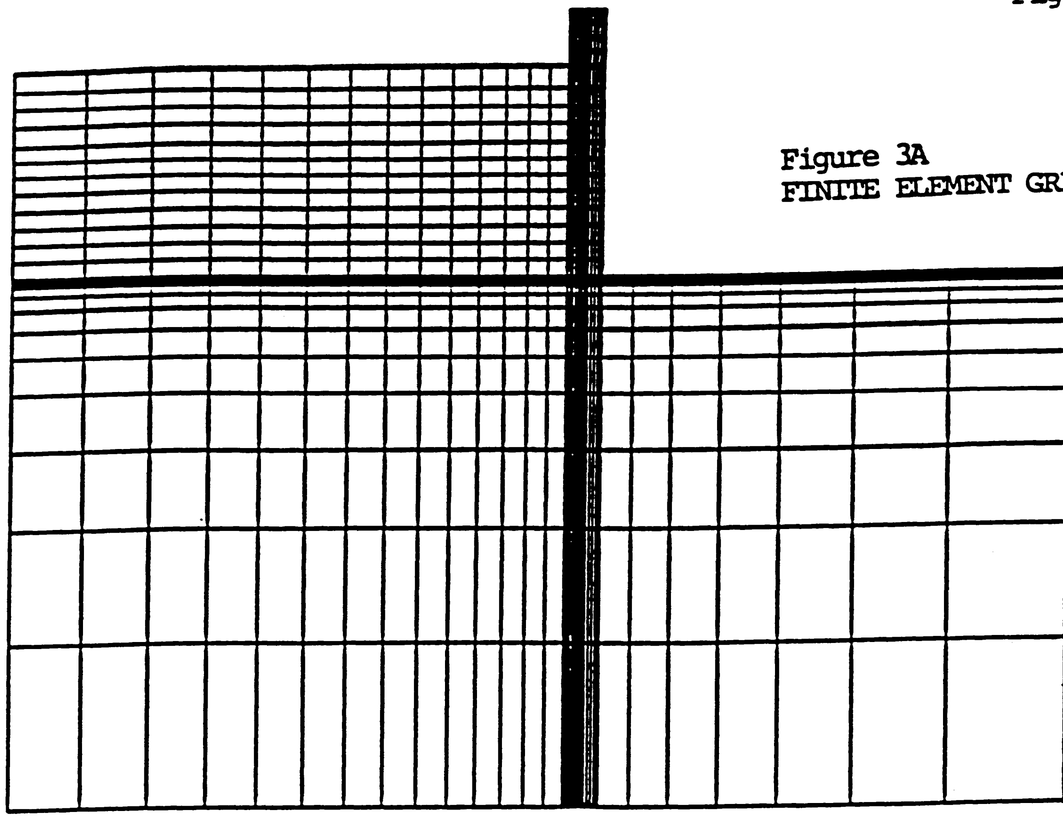

Figure 3A
FINITE ELEMENT GRID

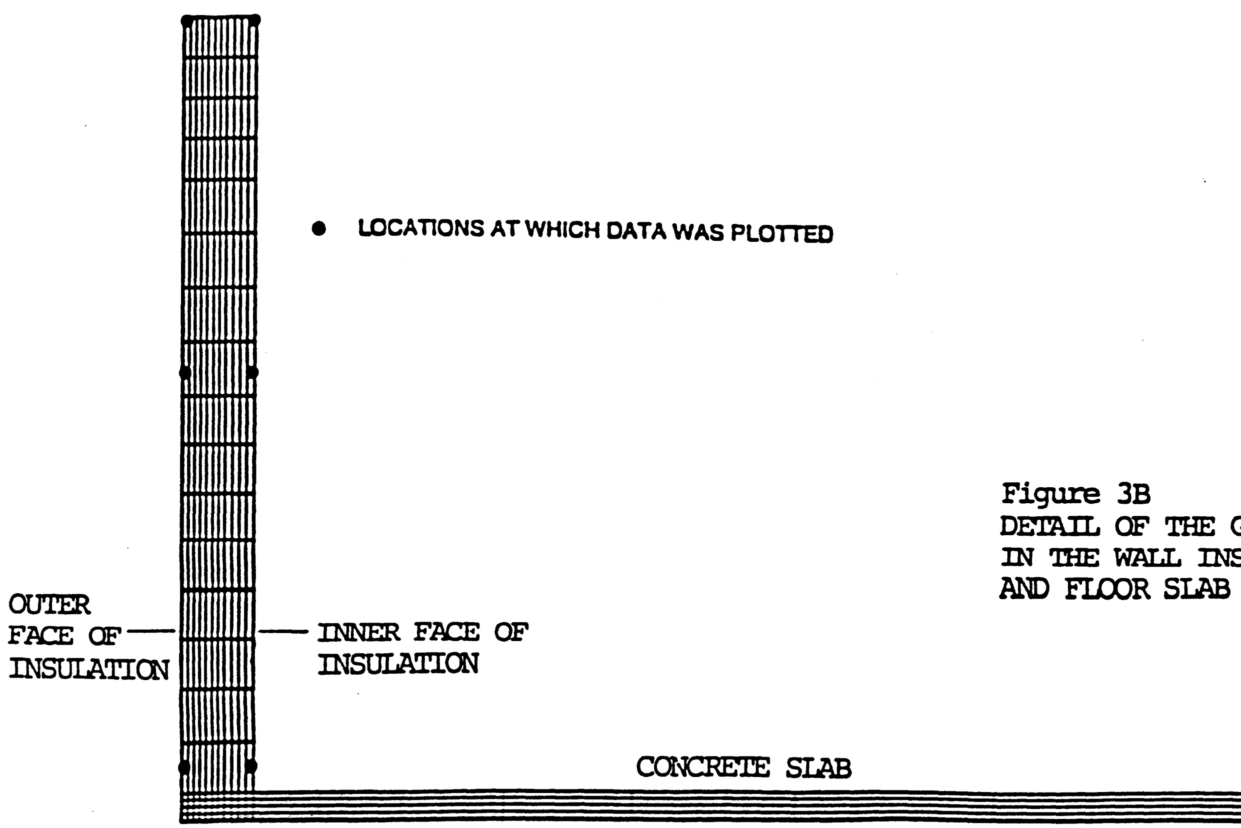

Figure 3B
DETAIL OF THE GRID IN THE WALL INSULATION AND FLOOR SLAB

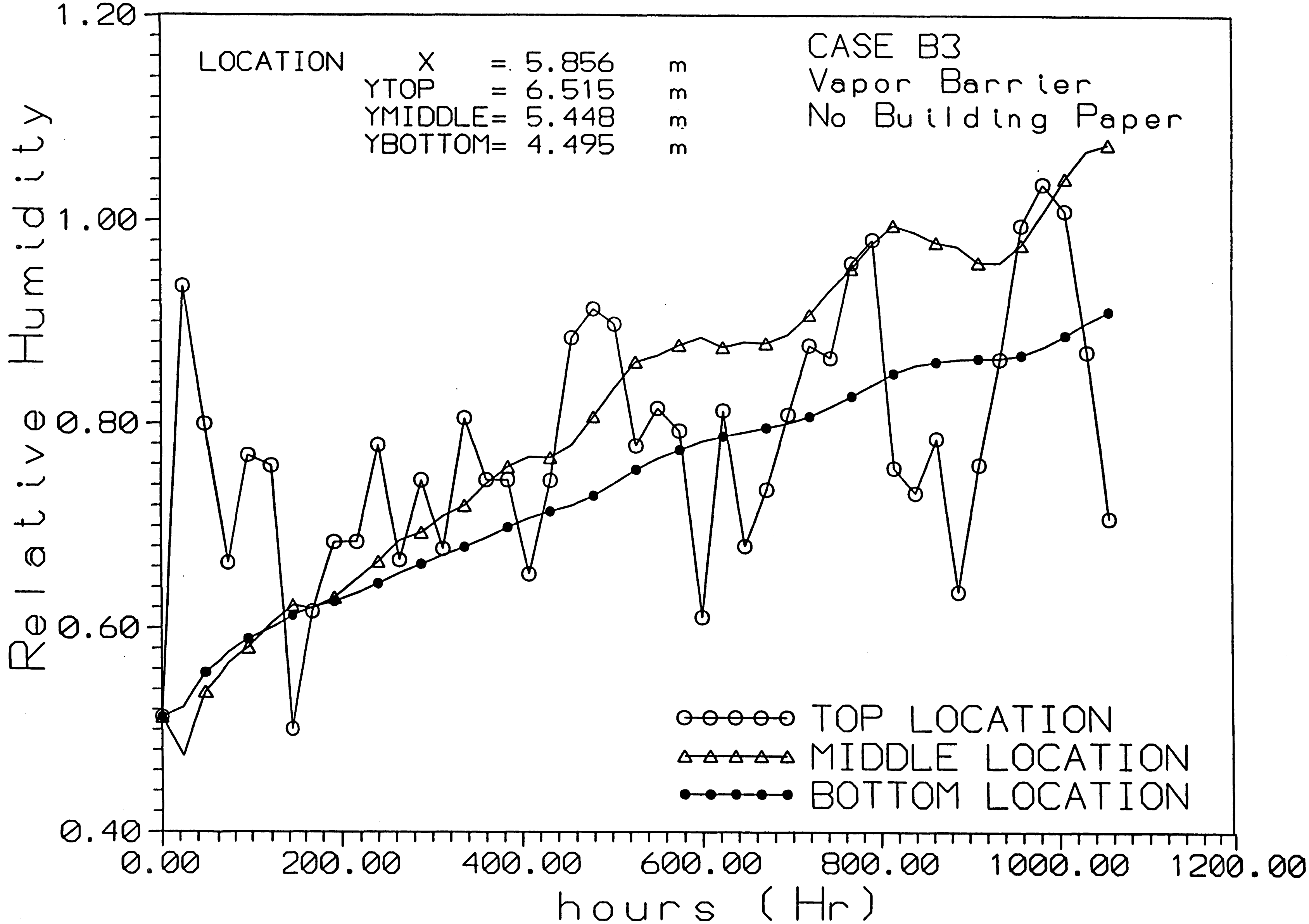

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Figure 4

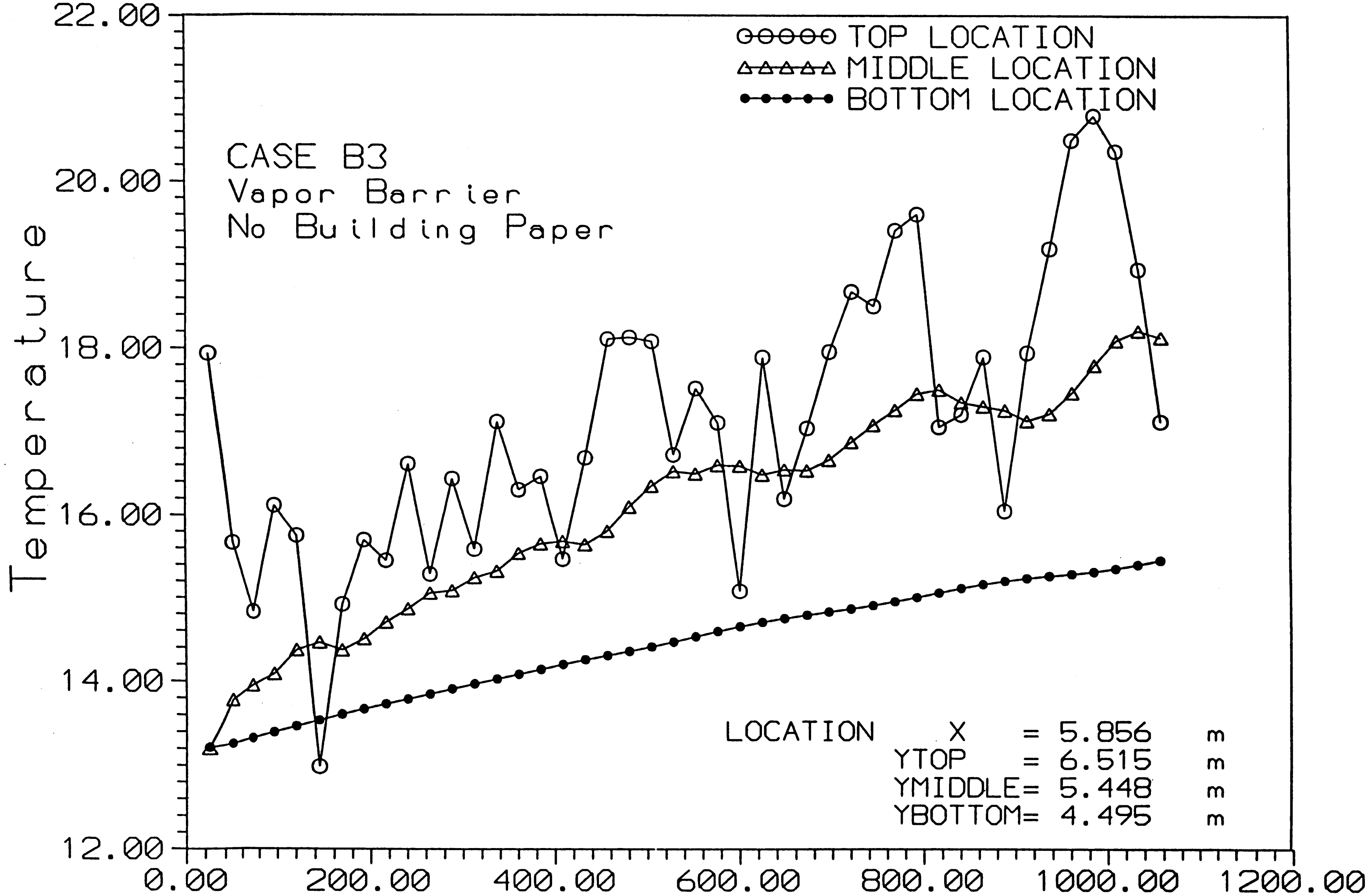
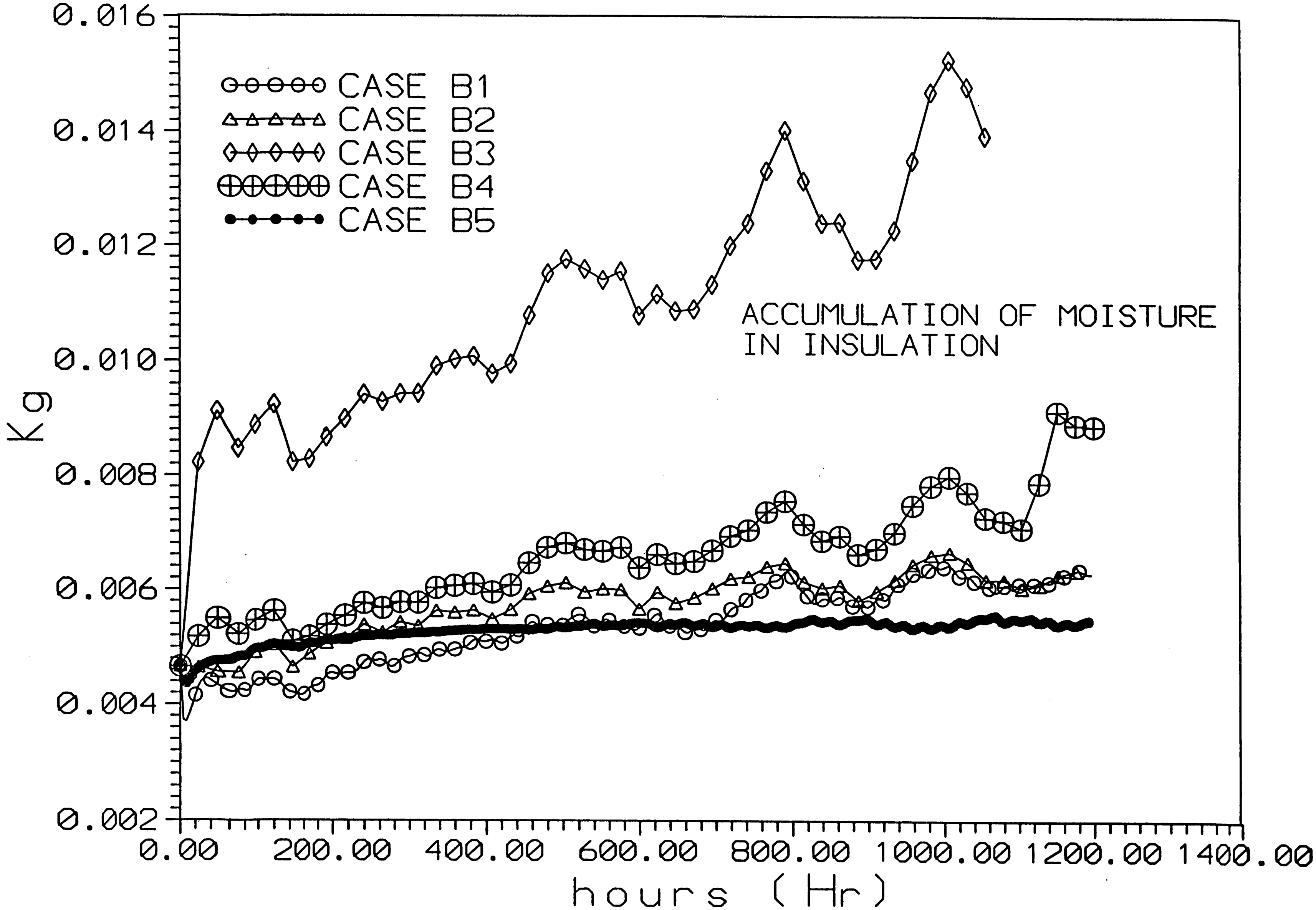

TOP LOCATION
MIDDLE LOCATION
BOTTOM LOCATION
CASE B3
Vapor Barrier
No Building Paper
Temperature
22.00
20.00
18.00
16.00
14.00
12.00
0.00
200.00
400.00
600.00
800.00
1000.00
1200.00
LOCATION X = 5.856 m
YTOP = 6.515 m
YMIDDLE= 5.448 m
YBOTTOM= 4.495 m

Figure 5


CASE B1
CASE B2
CASE B3
CASE B4
CASE B5
ACCUMULATION OF MOISTURE
IN INSULATION
Kg
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.00
200.00
400.00
600.00
800.00
1000.00
1200.00
1400.00
hours (Hr)

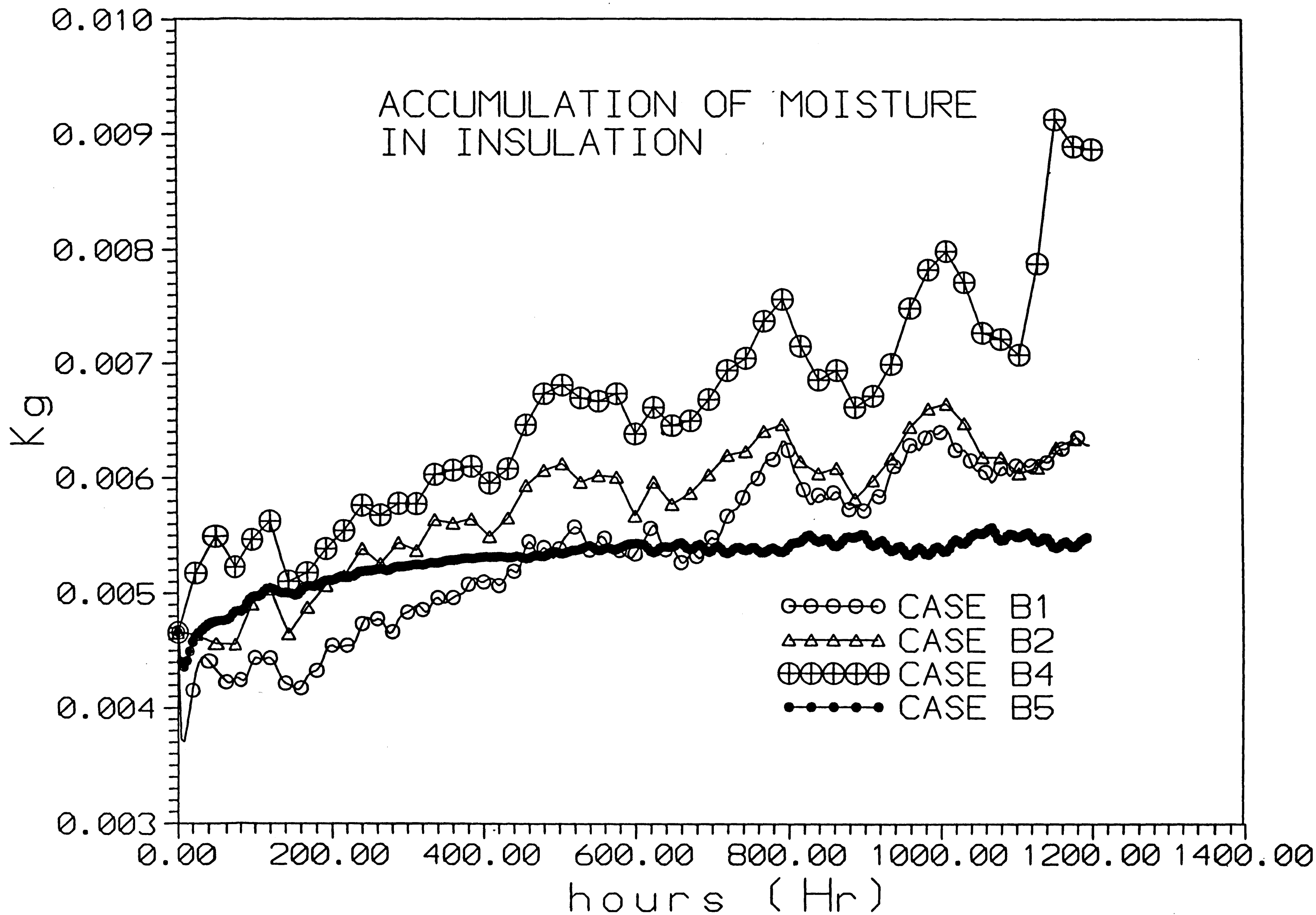


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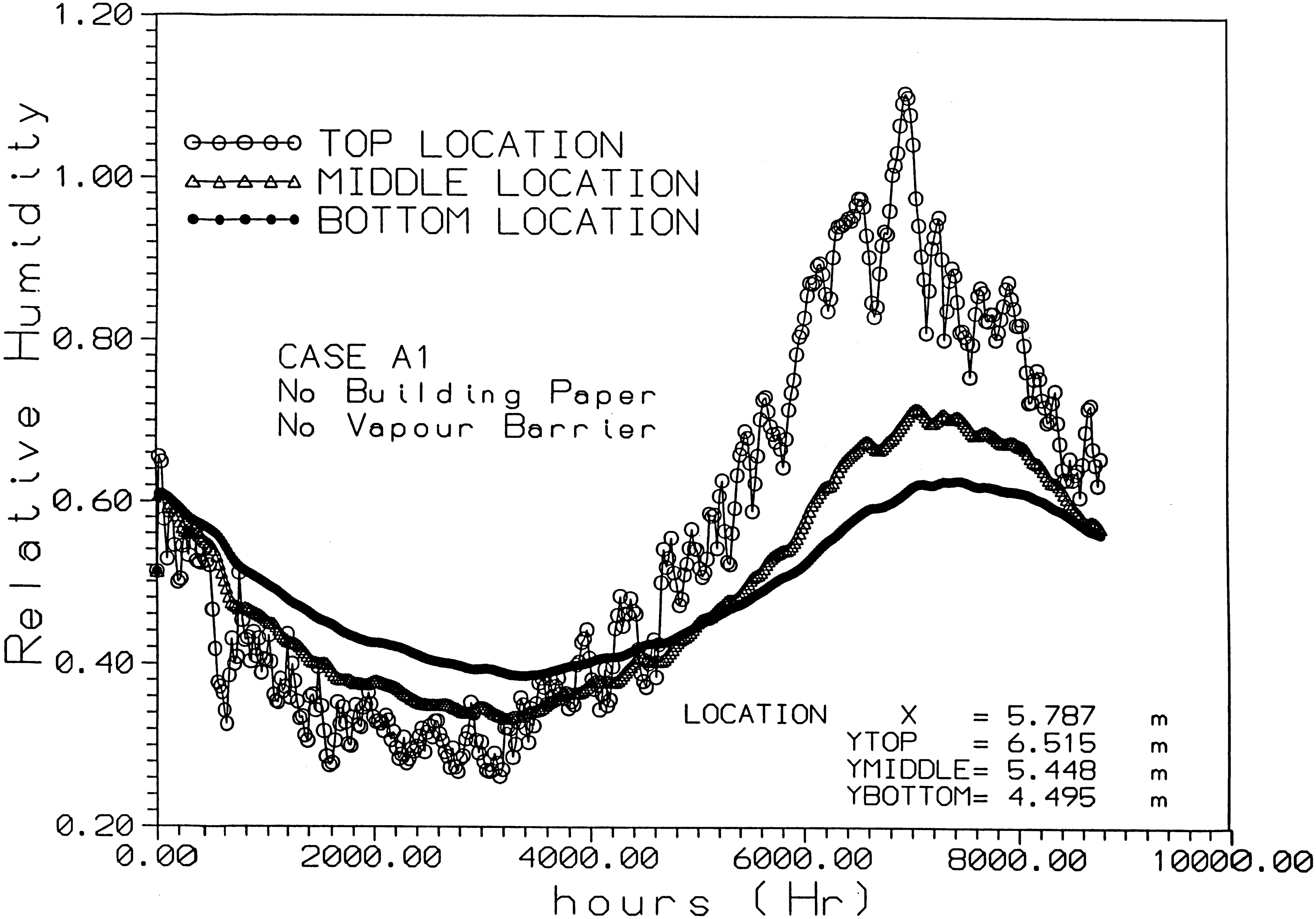
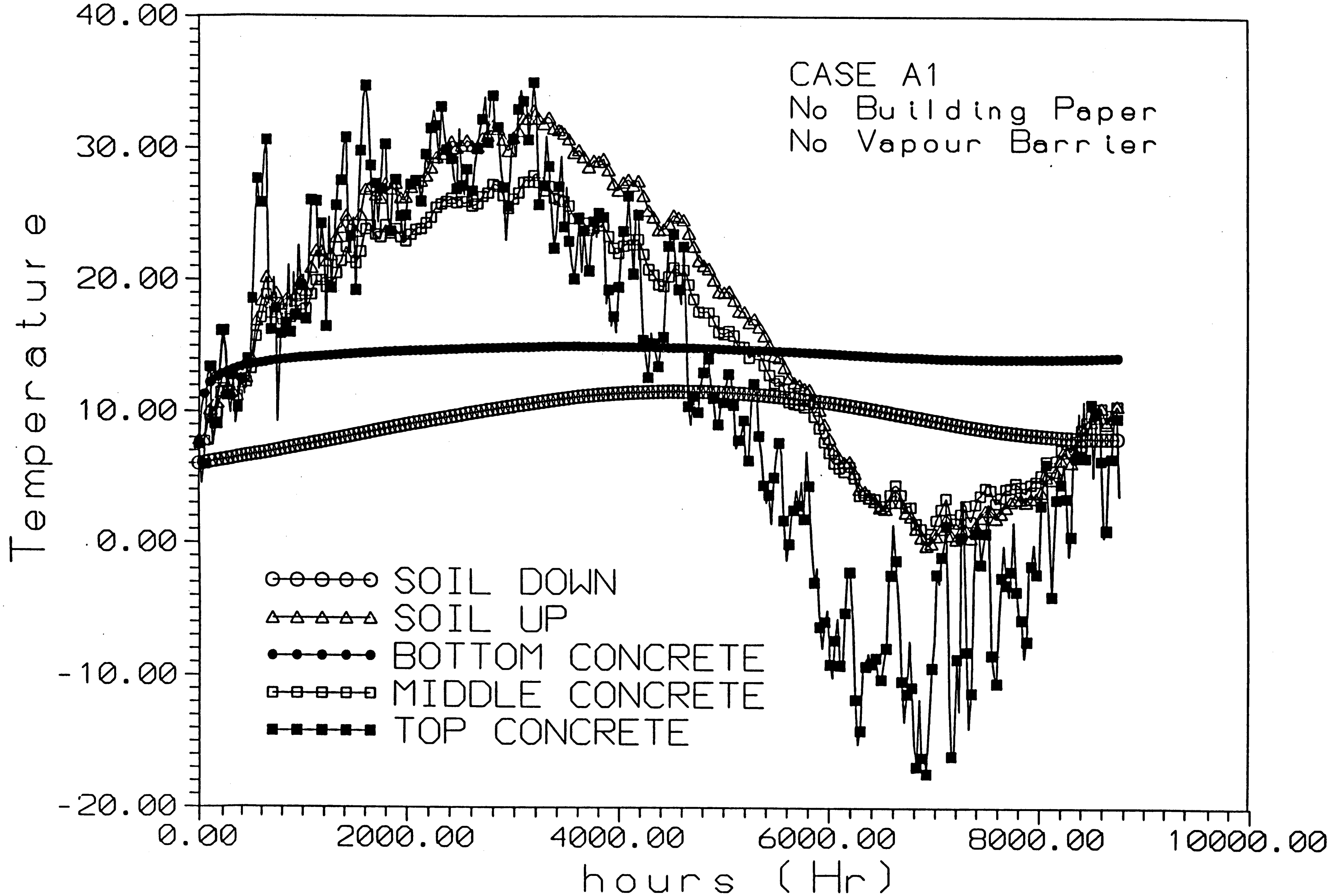
Figure 7



Relative Humidity
hours (Hr)
TOP LOCATION
MIDDLE LOCATION
BOTTOM LOCATION
CASE A1
No Building Paper
No Vapour Barrier
LOCATION X = 5.787 m
YTOP = 6.515 m
YMIDDLE= 5.448 m
YBOTTOM= 4.495 m
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2000.00
4000.00
6000.00
8000.00
10000.00

Figure 8



CASE A1
No Building Paper
No Vapour Barrier
SOIL DOWN
SOIL UP
BOTTOM CONCRETE
MIDDLE CONCRETE
TOP CONCRETE
Temperature
hours (Hr)
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
0.00
2000.00
4000.00
6000.00
8000.00
10000.00

Figure 9

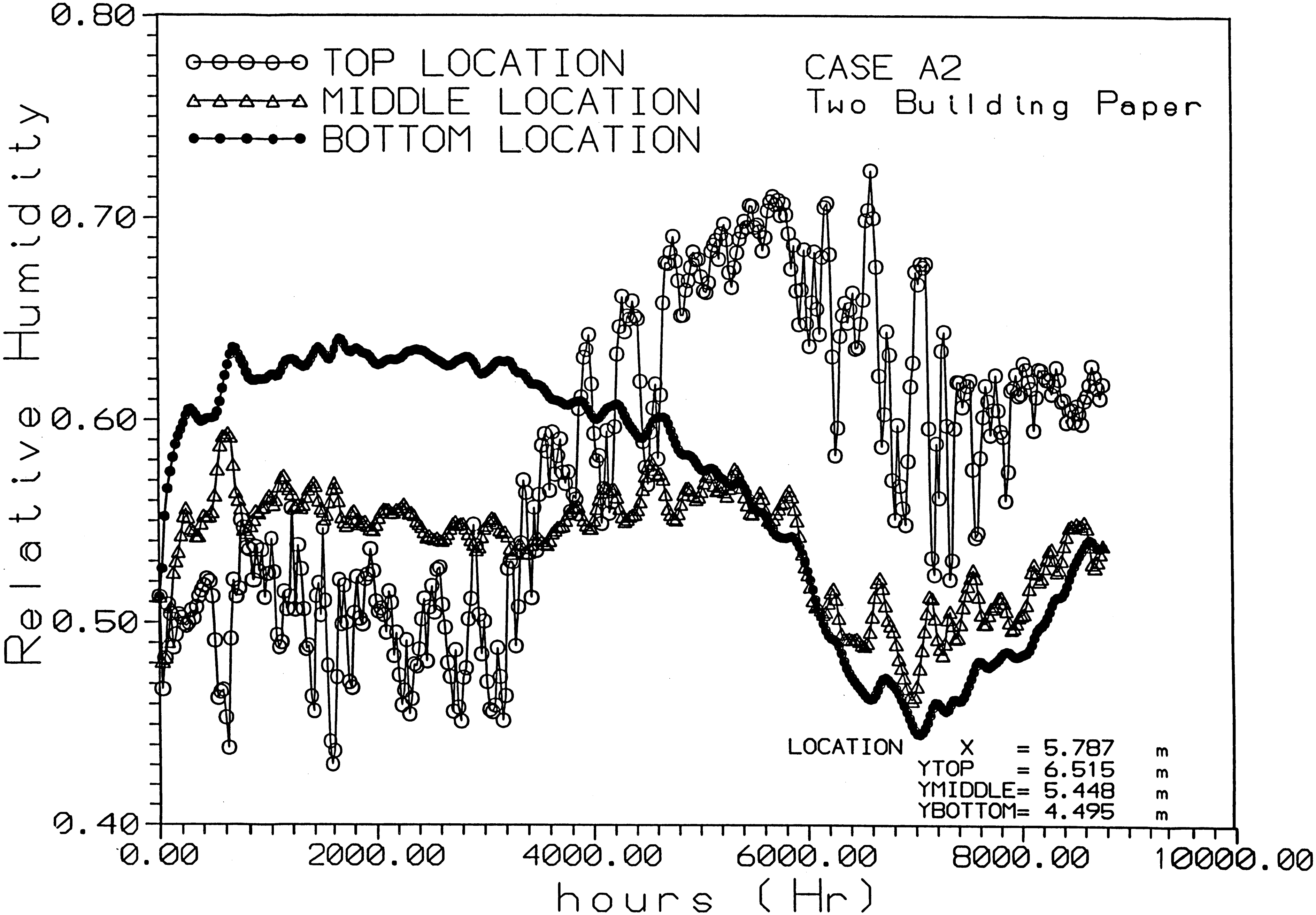


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Figure 10

APPENDIX A

SELECTION AND ADAPTATION OF A COMBINED HEAT AND MOISTURE FLOW MODEL FOR BASEMENT CONDENSATION ANALYSIS

INTRODUCTION

This appendix details the process of selection and adaptation of a combined heat and moisture flow model for the project "Development of an Interior Dampproofing Strategy to Prevent Basement Wall Condensation During Curing". The objectives of this project were to be met through the use of sophisticated computer modeling. A description of the selection process of the computer model is presented.

MODEL REQUIREMENTS

Detailed simulation of the condensation problem in curing concrete walls requires a sophisticated hygrothermal model. The complexity is inherent for this type of project since it is a 3-dimensional problem and it encompasses both vapour and liquid moisture transport. The concrete condensation problem is a transient process with complex material property dependencies which are both difficult to obtain and incorporate in the model.

The key modelling features required to research the basement condensation problem are:

- transient heat and moisture transfer formulation
- 2-dimensional spatial formulation (as a minimum)
- accounting for moisture capacity of the materials
- permitting variable material properties; e.g. as functions of material moisture content
- accounting for vapour transport
- accounting for liquid transport
- accounting for condensation and evaporation processes
- accounting for freezing and thawing processes
- accounting for the chemical combining of water during curing of concrete
- accounting for solar radiation incident on exterior surfaces of basements

As a result of IRC's ongoing involvement in the IEA (International Energy Agency) Annex 24 on Heat-Air and Moisture Transport in New and Retrofitted Building Envelopes, IRC staff kept up to date on the international state-of-the-art of hygrothermal models. Based on our review and understanding of existing models, it was concluded early in this project that no single existing model had all of the features needed to fully address the basement condensation problem. Nevertheless, it was felt that adaptation of an existing model to address the key features of problem was feasible, and that a more detailed assessment of model capabilities was needed to select the most appropriate model.

MODELS CONSIDERED

The following three numerical models were considered. Brief descriptions of these and their respective limitations are given below.

TCCC2D VTT/IRC MODEL

The **TCCC2D** stands for *Transient Coupled Convection* and *Conduction* in 2-Dimensions. It is a hygrothermal model developed for light weight constructions of multi-layer building structures. **TCCC2D** solves the heat, air and moisture transport and conservation equations that represent vapour transport flow and incorporates condensation/evaporation and freezing/thawing processes. The transport equations are based on temperature, pressure and water vapour pressure as driving potentials. It is a finite difference model, where the moisture content is coupled with the vapour pressure and temperature through the sorption isotherms.

Limitations

Limitations of the TCCC2D model are: the model can only be used for single rectangular component cross section, not complex geometries involving intersecting basement walls and slabs surrounded by a connected three dimensional boundary (the earth); the formulation is based on the vapour transport equations (liquid is not modeled); implementation of boundary conditions is very cumbersome; implementation of interface resistances is difficult; the implementation of moisture sources is difficult; and it is costly to run.

LATENITE MODEL

It is a recently developed IRC hygrothermal model for heat and moisture transport through macro porous and capillary type materials. The model is based on the Luikov type equations. The potentials for heat and moisture flows are temperature and moisture content respectively. To solve the full set of coupled equations, one can choose the finite element (Galerkin), Finite Difference or Finite Volume methods. A complex numerical procedure is used for calculating the moisture flow through the interface of two materials, since the moisture content potential can be discontinuous.

Limitations

The limitations in specifying basement wall and slab geometry are also present in this model; the specification of interface resistances such as vapour retarders or sheathing paper cannot be directly incorporated into the model; and the model cannot easily be adapted to input boundary conditions such as solar radiation and moisture sources.

FSEC (FLORIDA SOLAR ENERGY CENTER) MODEL

The **FSEC** model is a 3-dimensional general purpose software package especially designed to simulate complex building science problems. The program offers unique features. The major feature is its ability to solve user-defined systems of governing equations. Up to 250 coupled differential equations and their boundary conditions may be either selected from libraries or defined by the user. The use of finite elements allows the model to accommodate very complex structures and geometries, which is a very important feature in the basement condensation project. The moisture transport modules use the *evaporation and condensation theory*, assuming moisture travels due to water vapour density (partial water vapour pressure) gradients, local thermodynamic equilibrium exists, the total pressure is constant and the solid matrix is rigid. In a control volume (element) the net amount of water increase in the pores is equal to the amount of water vapour brought to the pore by diffusion minus the amount of liquid water accumulated. Additionally, the net amount of energy stored in the same control volume is equal to the amount of heat conducted plus the energy liberated during the phase conversion. Because at all times thermodynamic equilibrium prevails, the amount of liquid water at any given point can be calculated through the equilibrium sorption isotherm with the knowledge of the temperature and water vapour density at that point. The **FSEC** model has been applied to several moisture problems and good agreement has been found with analytical solutions.

Limitations

The major limitation of the **FSEC** model, as it was received, was the complexity of the input and processing modules. The use of finite elements augments the complexity of the supportive subroutines. In the current project the following were considered to be important limitations:

1. The material properties were unidirectional, i.e. thermal conductivity, vapour permeability
2. The model did not account for freezing/thawing processes
3. The vapour diffusivities, while strong functions of moisture content, were represented as constants.
4. Only vapour transport was modeled.

MODEL SELECTION AND ADAPTATION

The **FSEC** model judged to be the most appropriate for this investigation, due its flexibility and adaptability to the multi-layered structure of the basement project.

First Stage Adaptation - Steady State Heat Transfer and Verification

A benchmark study was also conducted to determine the predictive capabilities of the **FSEC** model when compared to **TWODEPEP** program. The **TWODEPEP** program is a 2-D finite element package developed by **IBM** which has been extensively documented and benchmarked. The **TWODEPEP** program has also been recently used by IRC staff for basement heat loss calculations. A set of basement energy loss calculations was performed using increasing amounts (in perimeter of the interior basement wall) of insulation. The basement domain was discretized into 2800 elements with higher element concentrations where greater temperature gradients prevailed (within the insulation, concrete and ground closest to interior basement). The grid distribution for one such case is given in Figure A1. In Figure A2 a comparison of the two models is shown. The results show the heat flux from the basement wall for a **R** value of 1.5. Very good agreement is found for all insulated floor wall segments; a good agreement is also expected for different wall insulation but no results were available for comparison. In summary, the **FSEC** model produced results within 3 % of the **TWODEPEP** program which gives confidence in the use of the model for the current project.

Second Stage Adaptation - Moisture Transfer under Steady State Conditions

Sorption Isotherms

An important property for hygric analysis of porous materials is the equilibrium sorption isotherm. The sorption isotherm curve is a plot the moisture content vs. relative humidity. In Figure A3 the sorption isotherms for *concrete* having the density of 2100 kg/m^3 is plotted based on data found in two references: one from the IEA moisture property handbook and the other from the FSEC model. The absorption curve from the IEA reference clearly is not correct at lower than 20 % relative humidity where moisture content values become discontinuous. The desorption values from the FSEC data base seem to be consistent, and thus will be used in this basement project. Figure A4 shows the sorption isotherm for *fiberglass* with a density of 18.40 kg / m^3. Figure A5 shows the sorption isotherm for ground soil with a density of 1840 kg / m^3. The equation used to describe the sorption isotherm is given as follows,

$$U = a\phi^b + c\phi^d$$

where U is the moisture content expressed as (kg/kg) and a, b, c and d are constants for a material. The sorption isotherms are also a function of temperature.

Moisture Vapour Diffusivities

The moisture vapour diffusivities are represented as constants in the present FSEC model Table 1 lists the moisture vapour diffusivities used as inputs to the model.

Material	Moisture Vapour Diffusivity $\frac{m^2}{s}$
Top Soil	1.25 E-6
Bottom Soil	1.08E-6
Concrete	1.20E-7
Building Paper	1.02E-11
Dampproofing Barrier	2.00E-12
Fiberglass	1.82E-5

Moisture Transport Under Steady State Boundary Conditions

Using a basement configuration the moisture and energy transport is simulated for steady state conditions as shown in Figure A6. The average temperature of the interior basement air is maintained at 20 °C with surface heat transfer coefficient of 5 $W / m^2 K$ and the relative humidity at 30 %. The outdoor air temperature is assumed to be constant at 12 °C with a ground surface heat transfer coefficient of 10 $W / m^2 K$. The vertical portion of the outdoor basement wall was exposed to a different surface coefficient of 14.9 $W / m^2 K$ and a solar radiation of 600 W / m^2. The ground temperature 12 m deep (from the ground surface) was maintain at 5 °C. The indoor air moisture content was kept at 0.001 (kg/kg), the outdoor air and the ground soil moisture content at 12 m depth was assumed 0.007 (kg/kg). For the calculation a surface moisture transport coefficient of 7.08E-3 (m/s) was used.

In Figures A7 and A8 the moisture content and temperature contour plots are shown for the steady state boundary conditions described above.

Third Stage Model Adaptation

The following steps were undertaken to complete the adaptation of the FSEC model:

- functional dependencies of thermal conductivity, moisture vapour diffusivity were included
- transient weather data modules were included, i.e. dynamic boundary conditions
- post-processing routines were developed to generate temperature and moisture content data, and to integrate data for analysis and presentation.

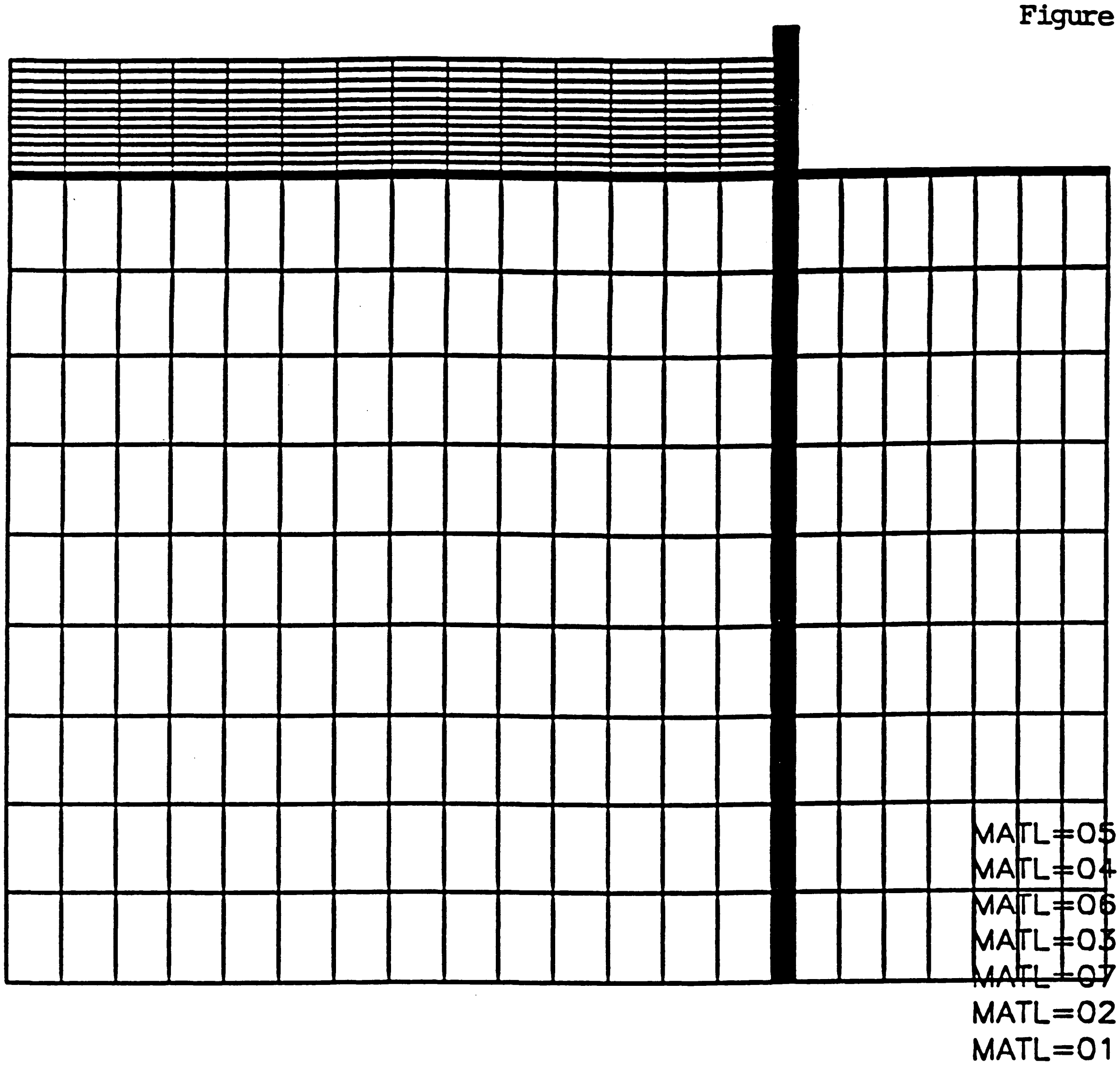

FIGURE A1. GRID LAYOUT FOR PROJECT

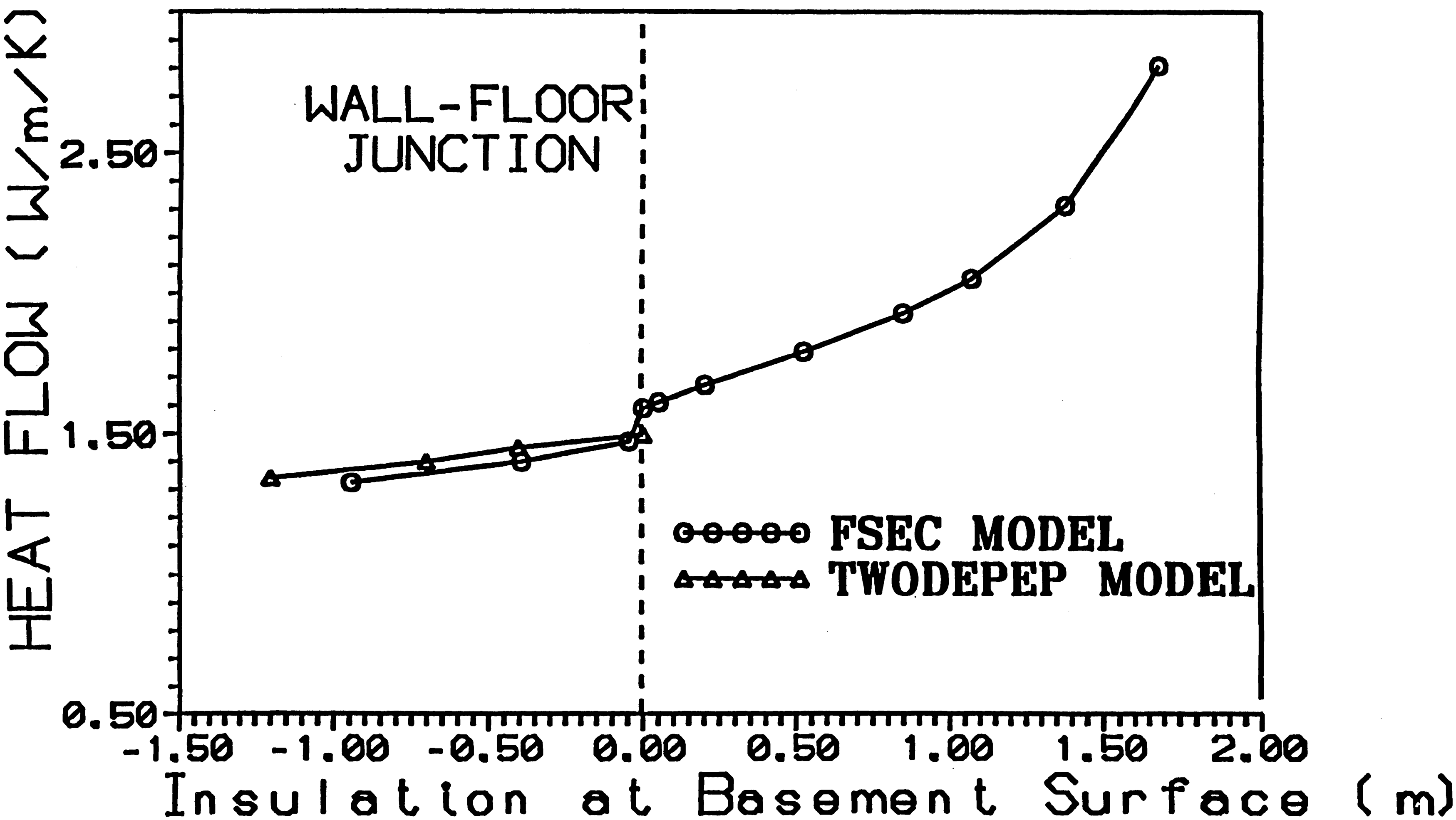

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Figure 2

CONCRETE SORPTION CURVES

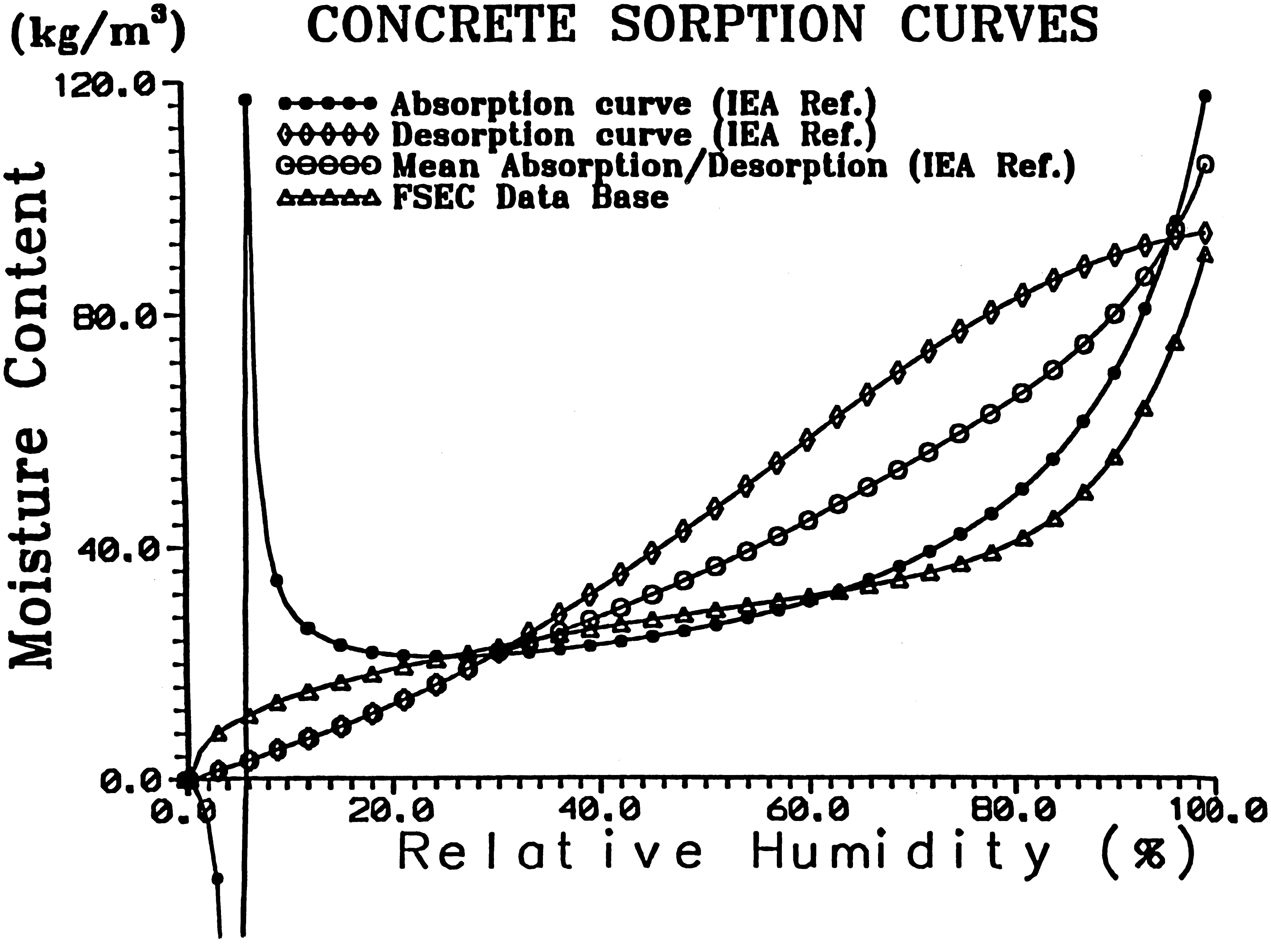

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Figure 3

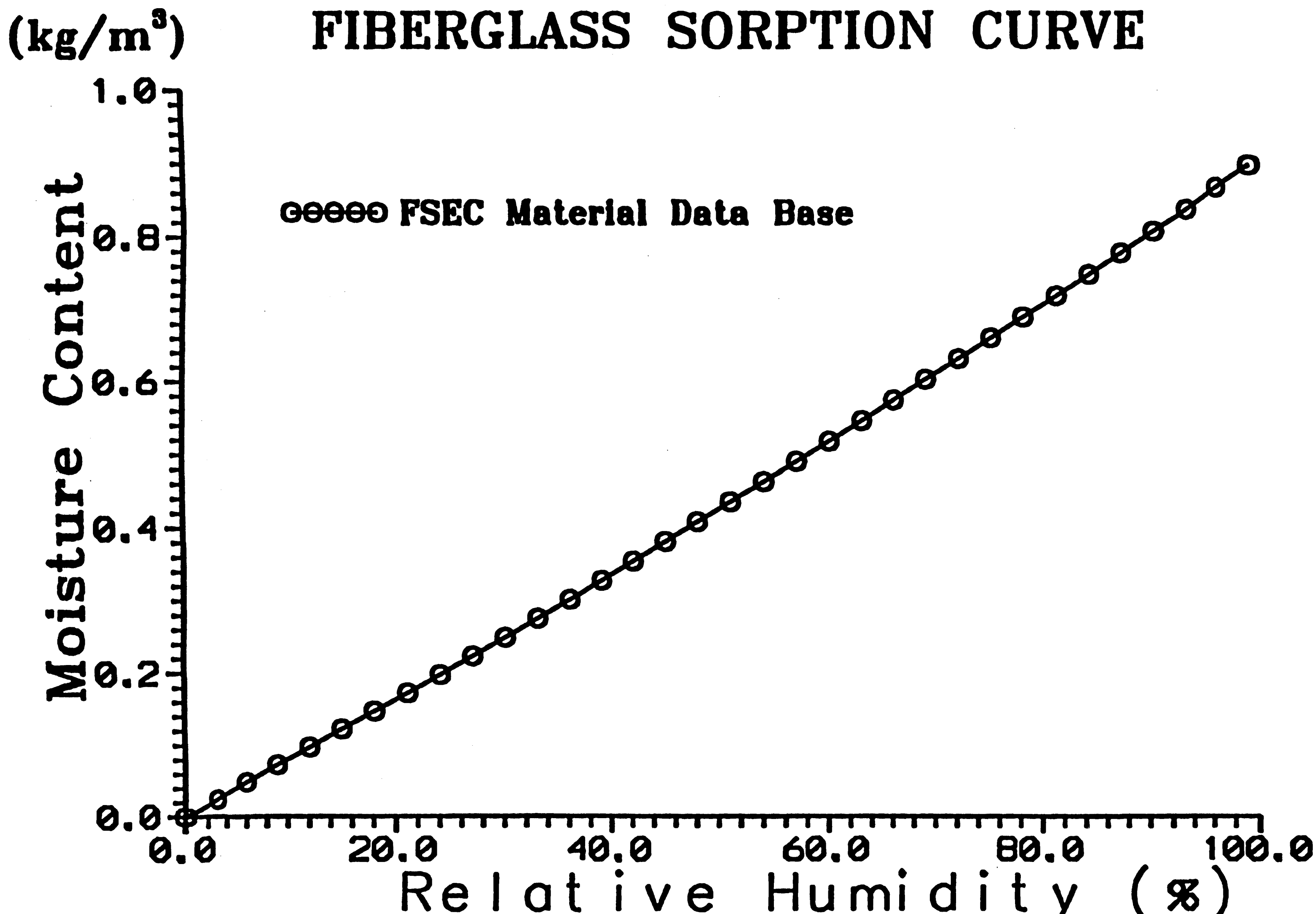

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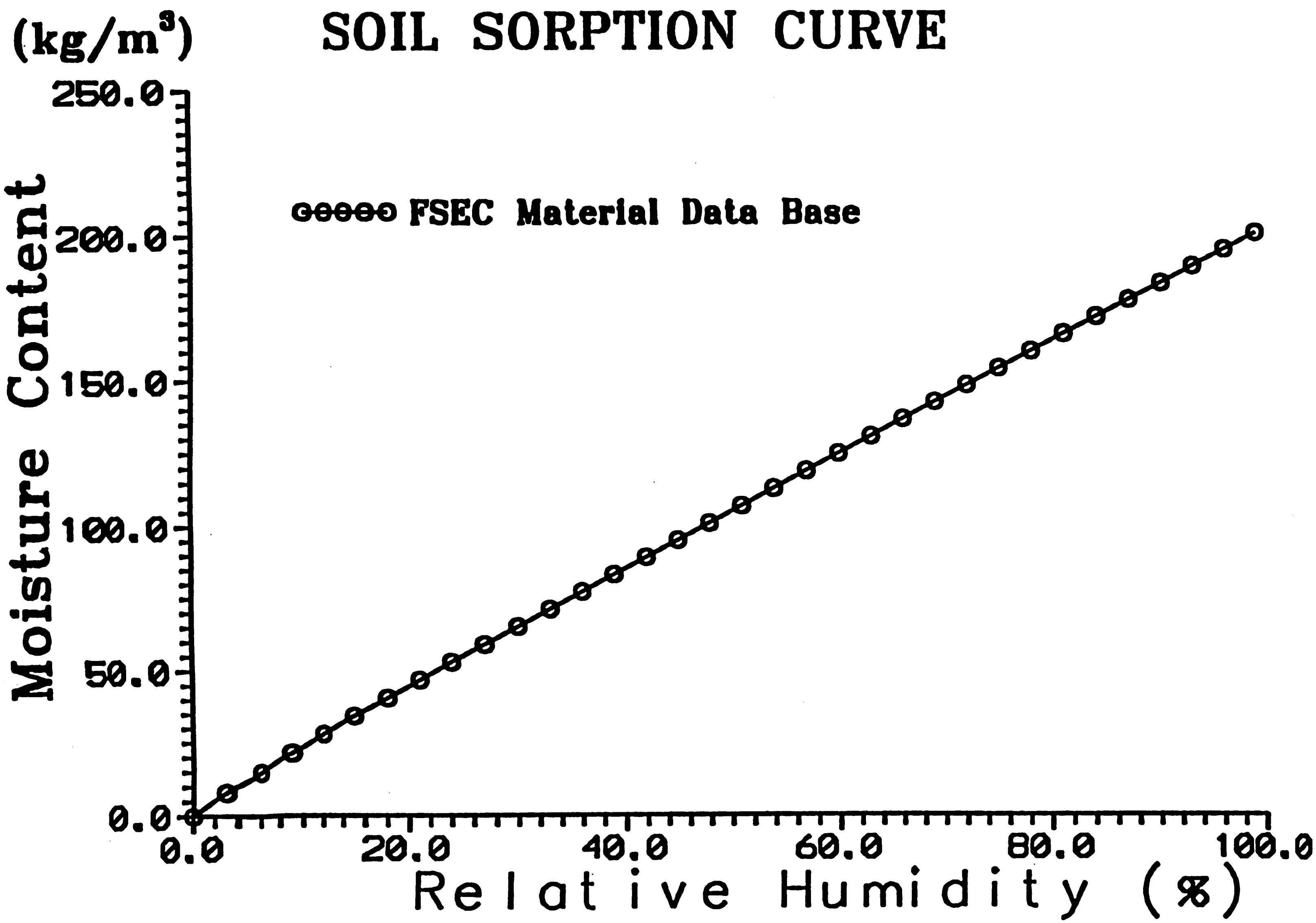
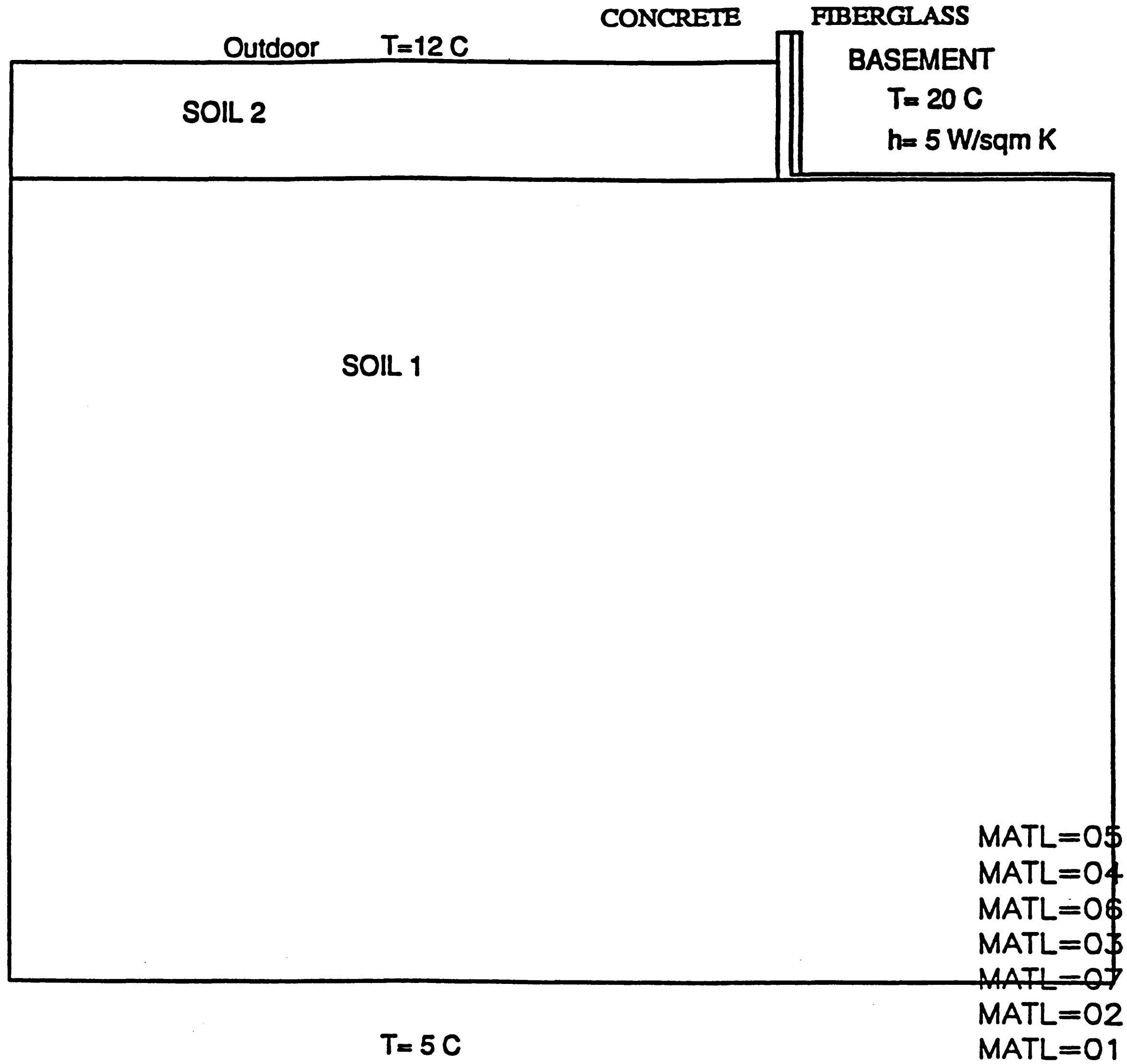
Figure 4


SOIL SORPTION CURVE
(kg/m³)
Moisture Content
FSEC Material Data Base
250.0
200.0
150.0
100.0
50.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
Relative Humidity (%)


CONCRETE
FIBERGLASS
Outdoor
T=12 C
BASEMENT
T= 20 C
h= 5 W/sqm K
SOIL 2
SOIL 1
MATL=05
MATL=04
MATL=06
MATL=03
MATL=07
MATL=02
MATL=01
T= 5 C

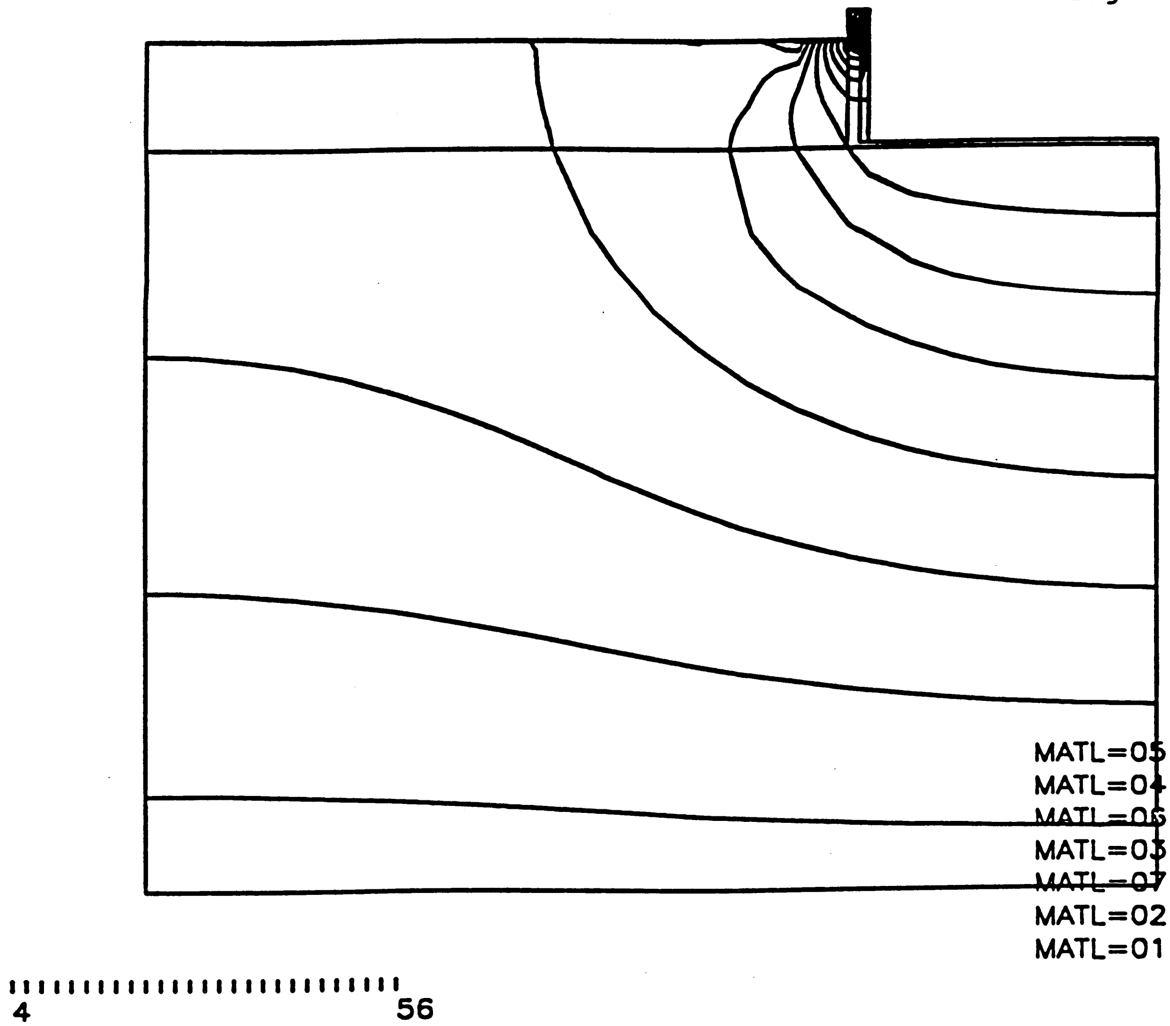


FIGURE A7. TEMPERATURE CONTOUR PLOT

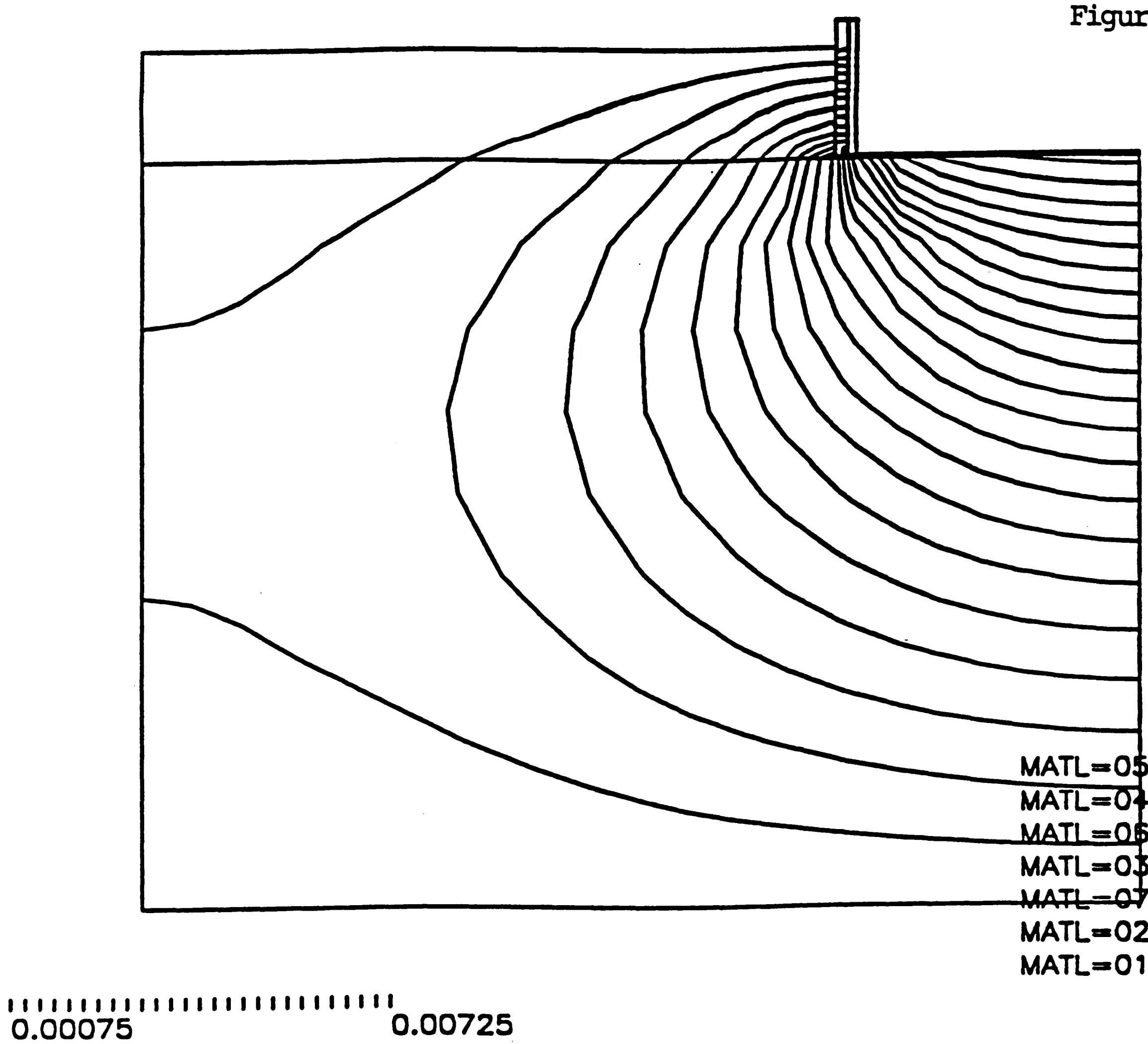


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FIGURE A8. MOISTURE CONTOUR PLOT