#6777

Building and Environment, Vol. 28, No. 2, pp. 221–228, 1993.
Printed in Great Britain.

0360–1323/93 $6.00+0.00

Test Cells: Do We Need Them?

JOHN LITTLER*

The argument is advanced that test cells are outdated for most purposes in building thermal design. Comparisons of one energy conservation technique with another are extremely dependent on the local weather. Because very small test-boxes are irrelevant, and reasonably sized test cells not transportable, simulation is seen as the vehicle to answer comparative questions. Computational fluid dynamic codes are in the position of thermal models 10 years ago. But they will gain preeminence over test rooms for the design of airflow and, particularly, natural ventilation systems. Component testing in scale models is seen as insufficiently sophisticated for most purposes. The vital areas where test cells remain essential, is for the improvement of model algorithms, the calibration of simulation models and the reinforcement of users' confidence in such models.

INTRODUCTION

THE VIEW taken in this paper, is that test cells are vehicles en route to validated simulation models. Scale models have a long and honourable tradition; but more up to date methods of evaluation are succeeding them in all cases where modern techniques are most cost effective. The discussion highlights some of these cases.

Scale models are very inflexible, once constructed they cannot easily be changed radically, thus the experiments conducted with them are necessarily and artificially circumscribed. The discussion mentions the changes of scale undergone by building models to illustrate the point.

Scale models are unfriendly. Unlike computer models they:

—are not transportable
—cannot be presented to clients as multiple examples with small component or system variations
—cannot be "played with" by designers.

The discussion suggests areas where these problems are causing physical models to cede to simulation models.

Test cells are expensive to replicate. This makes it difficult for several teams to work on the same problem, and makes it difficult to repeat experiments at a later date following structural changes to the cells, the need for which may come to light during their use.

The continuing major asset of scale models is that the results are "concrete" and demonstrable to the uninitiated; but as some of the test cell results show, to those in the know, this firm evidence is often quite ambiguous.

The other major asset possessed by test cells, namely the ability to model complex phenomena as yet unaddressed by computer based models, is disappearing, as the models become more sophisticated and users' confidence in their predictions increases. Conversely however, one of the chief methods by which computer models gain credibility, is by replicating measured results in test rooms. Some examples are presented.

The other aspect of thermal test cell use which has been emphasized in the past, is for testing components. It is suggested that this application is now dated and could be discontinued in the building arena. When deciding how to "test" a product, the criterion for whether to use a test cell or a simulation model could be expressed as some function of the costs and uncertainties of each technique. The balance is swinging away from test rooms towards simulation models.

DISCUSSION

Scale models have a long and honourable tradition

The most astonishing variety of scale models have been produced, including the well known Osborne Reynolds Apparatus and the Bump Testing Machine, not forgetting the Scheele Artificial Foot, which simulates the comfort of a foot in contact with a cold floor [1].

It is clear that scale modelling works extremely well for some purposes, and acoustics is a good example. In the case of auditoria, the acoustic solution is so central to the financial success of the building project, that adequate finance is available for testing, and the scale modelling does not become an end in itself; but is just one tool on the way to a solution of the problem.

The same comment applies to wind tunnel tests on aerofoil sections or car shapes.

Similar comments apply to daylighting studies in buildings, where physical scale models can be built cheaply and readily by students and professionals [2], the phenomena scale exactly, the total cost is a tiny fraction of the total design cost, yet the results are highly significant, well understood and easily transferred to the design profession. Daylighting models offer an added bonus not easily obtained with computer models—one can peer inside and show clients the nature of the illumination.

However, the same comments do not apply so readily to the use of test cells or test rooms in the evaluation of the thermal response of buildings. Practitioners do not see such a direct connection with the design process, and engineers are suspicious of the relevance of the results

---

*University of Westminster, Marylebone Road, London, formerly the Polytechnic of Central London.

when extended beyond the limited scope of a particular test room configuration.

Even more dubious is the application of scale models to thermal diffusion coupled with convective exchange, which is nearly impossible to model in scale without serious compromise to the basic physics.

Table 1 which summarizes the use of test cells, was published ten years ago [1]. In spite of large sums spent on test cells for the examination of building thermal response, the position has not moved on much, except in the very important area of "validating computer models". (In this paper, "validate" is meant to imply sensible, but not unhealthy, cynicism about the generality of models corroborated by limited comparisons.)

Considering the topics in Table 1 from the top:

—the work at Los Alamos on the comparison of designs, remain unsurpassed in its generality. (More is said about the Los Alamos programme below). Similar results on advanced glazing systems are not yet available, in part because existing test cells and rooms, are, with the exception of MoWiTT (about which more later), unable to deal with very highly insulating glazing systems.

—Martin and Watson [3] have studied some shading devices; but no general results are available.

—Studies on air flow, which was previously modelled at reduced scale with gases other than air (in an attempt to retain similitude), have been replaced by studies at reduced scale in saline solutions (discussed below), in scale models using laser Doppler anemometry and in real buildings where at least we can be sure that scaling problems are minimal.

Heat loss via walls etc. is being addressed by Hammond and Martin in respect of the important and neglected concern about heat exchange coefficients, with the use of test cells. This application highlights one of the few areas where great uncertainty still exists about the values which should be used in simulation models.

—Simulation models are now used to look at the dynamic response of buildings and the value of thermal mass.

—It is only in the area of "validation" that substantial progress has and is being made, and the reader is referred to Martin [4] and Lomas [5] for an up to date picture of the position.

—One may well start a discussion of test cells in the area of building thermal performance, by quoting from Reference 1 "... the advantages of test cells are that: they are unoccupied and well defined, they can be constructed easily to any specification (of insulation, air tightness, thermal load, glass:load ratio etc.). They are inexpensive, can be rotated and transported, and can be modified quickly to look at a new technique. In principle multiple zones can be studied but this facility has (by 1981), scarcely been exploited." The only one of these statements which has been borne out in practice, is that test cells are unoccupied.

Scale models are already giving way to simulation models

The unsurpassed amount of work on test cells carried out at Los Alamos Laboratories (LASL), between about 1975 and 1985, sorted out many of the issues involved in

Table 1. Areas appropriate for investigation using test rooms

	Successful experiments	Potentially successful	Less successful
Comparing designs:			
vented vs unvented mass walls	x		
isothermal vs non isothermal mass walls	x		
phase change vs non phase change walls	x		
mass walls vs direct gain	x		
direct gain vs attached sun space		x	
passive air heaters + floor storage		x	
Advanced glazing			
heat mirrors		x	
shutters, blinds etc.		x	
Daylighting and overshadowing	x		
Air flow:			
through doorways	x		
through vents, stairwells, corridors		x	
ventilation via windows	x		
infiltration via cracks			x
Thermal delay	x		
Validating computer models:			
for the general case		x	x
for special cases	x		
Thermal comfort		x	
Visual comfort		x	
Dynamic response of light and heavy weight buildings		x	
Heat loss via:			
walls and roofs	x		
floors		x	
Reducing wind speeds around buildings	x		
Simulating whole buildings		x	
Solar ponds and annual earth storage		x	

passive solar buildings, confronting designers in the US climate. The work divides into three sections:

- —side by side comparisons of various passive solar collection methods such as direct gain, vented and unvented mass walls, selective and matte black surfaces, night insulation and so on.
- —the experimental basis for the large simulation code PASOLE [6], which, via multiple runs and regression provided the widely used Solar Load Ratio method of calculation.
- —work on air flow within and between zones, stemming from air movement in two zone test cells with attached sunspaces, which formed the last element of the work at Los Alamos before the Solar Group was closed down.

The Los Alamos cells are shown in Fig. 1, and comparison with Fig. 2, which illustrates the SERC [7] test cells (subsequently the EMC test cells), demonstrates the derivative nature of most subsequent test cells.

The work at Los Alamos was largely distilled into highly accessible rules (for example rules for builders [8] concerning the balance between spending money on conservation or solar measures), and models for example the SLR method. The results were widely published in simple formats [9] and there is no doubt that the programme was highly influential in the field of passive solar design in the US.

Fig. 1. Los Alamos test cells, showing a variety of configurations.

Fourteen test cells were operated by Los Alamos, each having the same solar collection area and heat loss. Configurations included direct gain, unvented Trombe walls, water walls, phase change walls, sunspaces, self pumping freon collectors, naturally circulating air heaters, superglazing, night insulation and varying amounts of thermal mass [10–15]. The large number provided unparalleled opportunities for side by side comparisons under identical conditions.

There were precursors to the Los Alamos studies, for example, Hottel resumed work at MIT on solar energy in 1947, commenced before the 1939–45 War, and set up a laboratory which was essentially a series of test rooms. Figures 3 and 4 from Butti and Perlin [17] illustrate early experiments with water walls.

However in spite of this early work, it was not until the Los Alamos team made side by side investigations of water wall performance that designers could obtain clear guidance on the specification of a successful storage wall system. Some of the results are illustrated in Fig. 5 [18].

The Los Alamos test cells are open to criticism on the grounds of scale (measuring only 1.25 × 1.25 × 3 m high) and solar to load ratio (which was too high) and ventilation (which was not zero, was not continuously measured; but which in later experiments was fixed by forced ventilation at 3 air changes per hour).

However, these are minor criticisms, since the objective was not to provide impeccable data sets for model validation; but to allow broad guidelines to be drawn up covering the widely varying climates of the US, and concerning the solar fractions provided by each type of passive solar technique. If there is a drawback to the methodology, it is that attention was, as William Shurcliffe has pointed out, concentrated on solar fraction and not minimal annual purchased energy.

In practice, although the LASL work was not intended for model validation, several groups including, Arume Noe's (authors of DEROB) at Austin [19], have so used it.

Figure 6 shows the cells of Fig. 5 simulated [20] using Apache [21]. As the Apache simulations suggest, the broad conclusions about the benefits of various passive solar techniques (or insulation measures) can now be drawn for the different climates using modern simulation tools, and the use of test cells for such purposes is both unnecessary and too costly. The agreement between simulation and measurement is not perfect. (Denver TMY weather was used since on-site data was not available, and water walls are currently ill-simulated since heat transfer within them is convective as well as conductive, this problem will be addressed in later papers by using FLOVENT). But the lack of precise agreement is not of concern in this context, designers seeking information about the relative value of mass walls are not concerned with accuracy to the last milli-Kelvin, but rather the broad conclusions.

However, it is significant, in the light of discussion about the validity of using test room measurements to draw conclusions about comparative tests, that different weather conditions give rise to different comparative results. Figure 7 shows LASL results on the same cell configurations for various periods with differing weather conditions. Two points can be made:

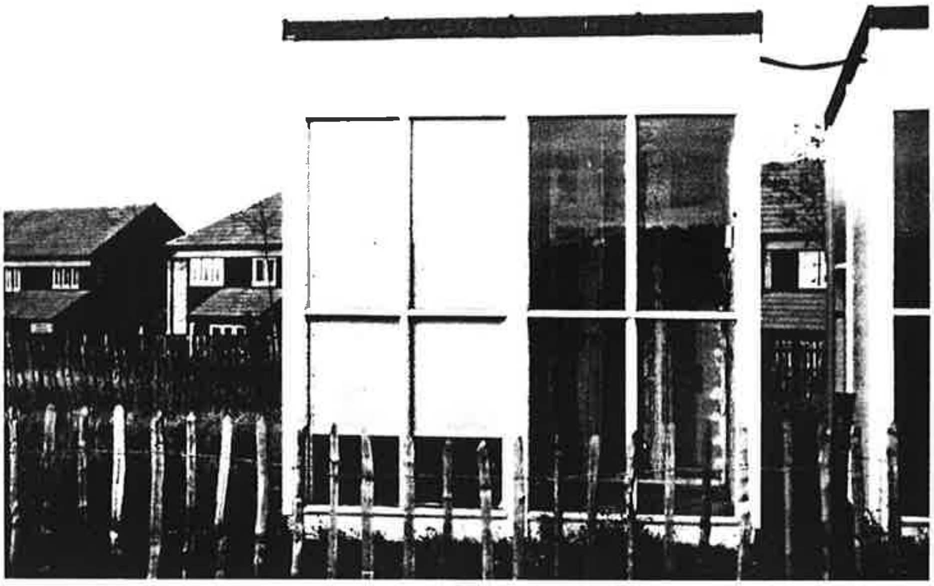


Fig. 2. Polytechnic of Central London test cells, showing edge sealed blinds on test, selectively coated and black painted mass wall.

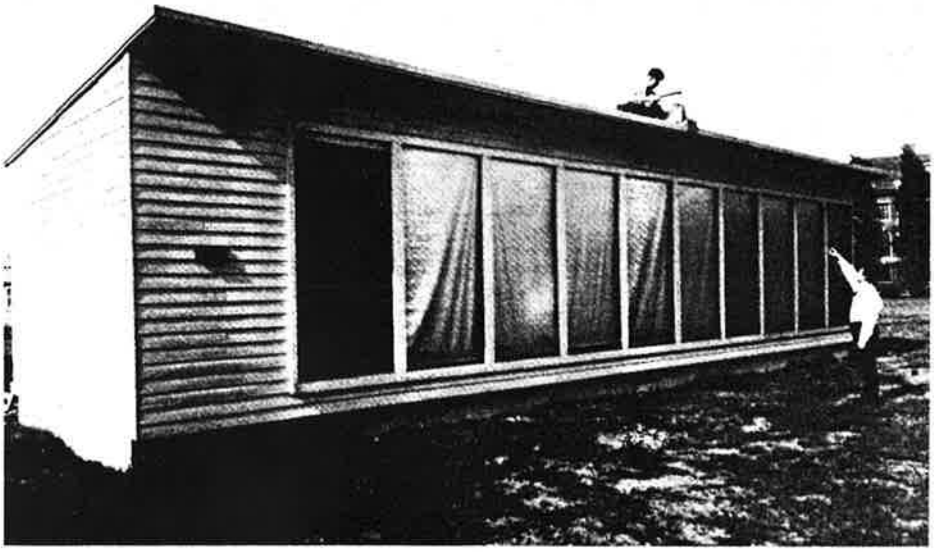


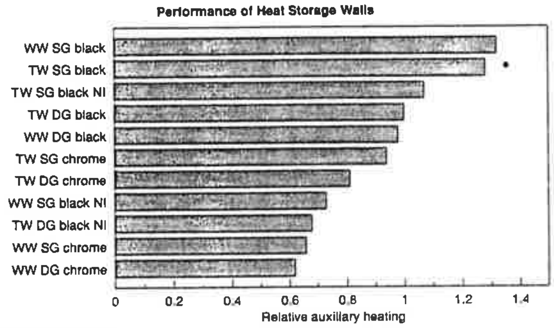
Fig. 3. South wall of the laboratory used by MIT for its experiments with water wall solar collectors, insulating curtains are drawn in all but one unit.

1. The influence of real weather is strong and thus tests conducted indoors under electric lights, with absolutely no relationship to real weather, are unhelpful, and
2. The broad conclusions remain roughly the same from one test period to another, but quantifying the benefits of one technique for saving heating (e.g. selective surfaces as compared to black paint) is probably better carried out with "calibrated" simulation models, using local weather data, than with the results of test cells in climates differing from that for which results are sought.

Scale models will give way to simulation models

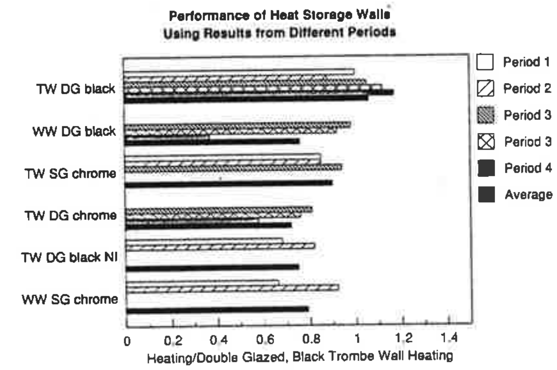
The LASL cells were not designed to study air movement and ventilation. Towards the middle of the LASL programme, Colorado State University built the REPEAT (REconfigurable Passive Evaluation and Analysis Test) facility [22] one of whose main aims was to study air movement in passive solar buildings under realistic conditions. The Los Alamos group took the decision to make their measurements on air movement in real buildings and again produced as a result a set of rules of thumb. REPEAT was at full scale thus avoiding similitude problems for air movement, and studies were

Fig. 4. Inside the laboratory control room a student monitors the instruments.



Data from Hyde ref 18
TW=mass wall; WW=water wall; black=flat black;
SG=single; DG=double glazed; chrome=selective

Fig. 5. Side by side tests at Los Alamos of painted and selective surface storage walls. [The selective surfaces were applied to the outer sides of the unvented mass walls and the water walls. The water tubes were sealed one to another forming an imperforate barrier]. Plotted by comparison with an unvented Trombe Wall, double glazed and painted black.



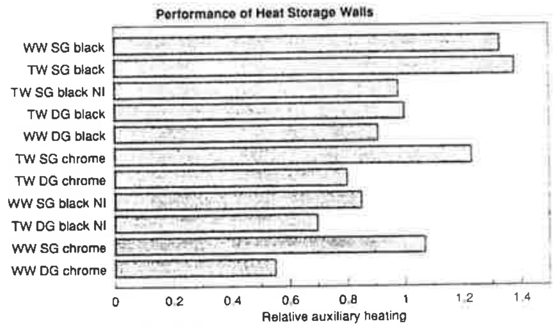
Data from Hyde ref 18
TW=mass wall; WW=water wall; black=flat black;
SG=single; DG=double glazed; chrome=selective

Fig. 7. Comparative LASL test cell results, for different times of the year [the comparison is between the auxiliary heating necessary in the test configuration, compared with that in a double glazed, black painted mass wall configuration].

made of ventilation within and between zones disposed both vertically and horizontally.

The history of outdoor test cells has been through a complete cycle of sizes, from MIT's experiments with full size rooms, to early work with 1 × 1 × 1 m boxes, to LASL cells with typical dimensions of 2 m and back again with REPEAT to full sized rooms. The PASSYS programme represents a compromise in size between LASL and REPEAT. The complexity and cost of large test rooms militate against high productivity in terms of results. This has been a driving force in the search for accuracy at small scale. A search which looks increasingly unproductive.

The group at CSU chose to work at full scale for the observation of air movement, after a lot of effort had gone into reduced scale modelling at CSU, LASL and Lawrence Berkeley Laboratories. Authors have tried a variety of approaches to similitude, using models at approximately 1/10th scale filled with Freon 114 and Freon 12 [23], water [24], saline solutions [25] and reduced scale models filled with air [26]. The experimental skills and thus costs are quite high, for experiments which involve gas or water-tight enclosures complete with either methods for injecting saline concentration gradients or uniformly heating one end of a cell and cooling the other.



Calculated with APACHE NI=night insulation;
TW=mass wall; WW=water wall; black=flat black;
SG=single; DG=double glazed; chrome=selective

Fig. 6. Simulations of painted and selective surface. storage walls [simulations were carried out using March 1965 TMY data for Denver].

There is very little evidence to indicate whether scale models give accurate answers, since very few comparisons have been made with measurements in real buildings. It is generally considered that models at 1/10 scale allow predictions to be made about natural air movement. For example the Hanse Viertel shopping centre in Hamburg was so designed [27]; but the chosen scale is a compromise between cost and (unknown) inaccuracy. One of the rare confirmations is provided by the LASL predictions of convective heat flow via doorways [23] which agree well with later measurements made in passive solar buildings [28].

Recently, computer fluid dynamic models (CFD) have become accessible through the use of better data input methods and much cheaper processors. The cost of a CFD model is less than that of a single experiment in a scale model of a new building and clearly the computer technique is infinitely more accessible to engineers. However there is as little validation of the computer models as there was of the scale modelling technique.

Whilst test rooms are excellent for enhancing confidence in thermal models, they are not so useful in the corroboration of CFD models dealing with natural air flow, where similitude problems introduce such an element of confusion.

The use of scale models to test components may already be outdated

The Mobile Window Test facility (MoWiTT) [29] at the Windows and Daylighting Group at Lawrence Berkeley Laboratories, the Room Calorimeters [30] at the National Bureau of Standards Washington and the Passive Systems test cells in the European Community Programme (PASSYS) [31], all followed dissatisfaction with existing methods of component testing. They have concentrated on testing products rather than buildings.

Hosing down a window to test its seals against rain remains a valid and useful test for the consumer. It is limited to the window in its frame and does nothing to address the serious problem of leakage between the frame and the wall. Similarly, hot plate tests of glazing conductance provided very limited information on how well a window would perform in a building. Guarded hot boxes in which air is blown at the window in an unrepresentative fashion, do go some way towards increasing the realism of the test. Indoor test boxes illuminated with halogen lights which fail to approximate the infra red and visible components of daylight and sunlight, fail to simulate outside air flow and fail to represent night skies, add little to our knowledge about the performance of components such as windows in real buildings and it was not until the advent of MoWiTT that proper testing could be done. In some senses, MoWiTT has challenged US manufacturers to produce better windows with lower U values, because the facility was designed with advanced measurement in mind, and it is thus able to assess very highly insulating systems by measuring U values as low as 0.5 W/m^2 K with an accuracy of about 0.1 W/m^2 K. The PASSYS test cells on the other hand were designed to carry out a variety of tasks, and problems of thermal bridging, control and large fabric heat loss conspire to impair accuracy at very low U values.

One of the outstanding contributions made by MoWiTT has been the extensive validation afforded to the Windows and Daylighting Group's model of window performance called WINDOW [32]. The model surpasses window treatments in current building simulations and has been recommended as the precursor to the use of SERI-RES in the UK [33]. In recent tests (shown in Table 2), it was gratifying to see almost complete agreement between simulations carried out using WINDOW. the Canadian model VISION [34], the Pilkington model MULTB, long term regression data from two years of monitored data in a project with superglazed windows and short term measurements using heat flow sensors at night [33].

As McCluney points out [35], scale model test situations are increasingly unable to provide representative performance characteristics for complex fenestration situations and (echoing comments from Lawrence Berkeley Laboratories) these are best dealt with by a com-

Table 2. Comparison of *U*-value and shading coefficient results from the various assessment methods used

	S.G. blinds closed		S.G. blinds open		S.G. blinds pulled up		Triple. 2 low-e		Double glazed	
	U	SC	U	SC	U	SC	U	SC	U	SC
MoWiTT (test cell)	0.89 ±0.13	0.26	1.03 ±0.20	0.22	1.19 ±0.12	0.48	1.13 ±0.13	0.62	2.4 ±0.4	0.8
Tait Solar (hot plate)	1.08		—		1.25		1.42		2.38	
DSET (solar simulator)		0.30		—		0.48		0.58		—
EMC heat flow mat (*in situ*)	0.95 ±0.07		—		—		1.07 ±0.07		—	
Polystyrene slab (*in situ*)	—		—		0.84 ±0.09	—		—		
WINDOW 2.0 (simulation)	—		—		0.98	0.45	1.10* ±0.01	0.52	2.47* ±0.07	0.87
MULTB (simulation)	0.96	0.13	—	—		0.47	1.14* ±0.03	0.52	2.55* ±0.17	0.84

NB. Simulation assessments are with frame corrections.

Key: * = simulation driven by MoWiTT data recorded during corresponding test. Otherwise. simulations are for ASHRAE Winter Conditions.

SC = Shading Coefficient. U = U-value in W/m^2 K, S.G. = superglazing.

bination of laboratory measurements of optical properties and simulation modelling.

The use of scale models to improve computer models remains essential

The obvious area where test rooms remain extremely powerful, is as a test-bed for specific algorithms. The work of Hammond *et al.* in the UK concerned with evaluating surface heat transfer coefficients, work at British Gas on the system response of thermostat, heating plant and building fabric, and the MoWiTT studies provide good examples.

The received view is that simulation models cannot be validated against measurements in real buildings. To some extent this view derives from the first and disastrous attempt in the Collins building [36]; but techniques for monitoring have progressed, and at least two recent studies of "Class A" monitored buildings [37, 38], have allowed corroboration of simulation models. Possibly it is time to review received opinion on this matter.

CONCLUSIONS

Test cells have no zoom facility. For example, the thermostat system problem alluded to above, revolves around time constants of controls and fabric, which can be changed easily in a simulation model—the time scale over which observations are made can be expanded or contracted at will; but they cannot be so easily altered in a test cell. Test cells cannot be used to investigate the value of components not yet available. For example it is possible to simulate the performance of highly transmitting photochromic glass, but none yet exists.

Scale models are unfriendly, unlike computer models they are difficult to change, inherently limited, expensive, and they cannot be used by the engineer in his or her office. In some cases, such as photographs or videos of beautifully made scale models in the area of daylighting, models are useful as vehicles to illustrate complex dynamics; but even here, the advances in rendering and graphics boards seem likely to eclipse the use of physical models. As so often happens the building field lags behind the automotive industry, where 3D projected holograms of cars which the senior executives can walk around are taking over from the laborious craft of clay or wood models.

The single vital area where building thermal test cells remain essential, is for the refinement of specific algorithms.

REFERENCES

1. J. Littler and M. Watson, Passive Solar Design, Scale Models and Component Tests, Report to the Energy Technology Support Unit, U.K. Department of Energy (May 1981).
2. F. Moore, *Concepts and Practice of Architectural Daylighting*, Van Nostrand-Reinhold (1985).
3. C. J. Martin and M. Watson, in a series of reports to the UK Department of Energy via ETSU, concerning measurements made in the Energy Monitoring Company (EMC) test cells, 1985–91. (These and other Reports from the Department are obtainable from: ETSU, Building 156, Harwell, Oxon OX11 0RA.)
4. C. J. Martin, Detailed Model Comparisons, an Empirical Validation Exercise Using SERI-RES, Report to the UK Dept of Energy ETSU 1197-G (December 1990).
5. K. J. Lomas, Dynamic thermal simulation models of buildings: new method for empirical validation, *Bldg Serv. Eng. Res. Technol.* **12**(1), 25–37 (1991).
6. W. O. Wray and R. D. Mcfarland, PASOLE a general simulation program for passive solar energy, Los Alamos National Lab report LA-7433-MS. (LASL Reports are available from Los Alamos National Labs., Los Alamos, New Mexico 87545 USA).
7. Four test cells operated for the Science and Research Council by the Polytechnic of Central London (1983–85).
8. J. D. Balcomb, Builders Guidelines, *12th National Passive Solar Conference*, *Portland* 1987, p. 403, published by the American Solar Energy Society (Bolder, Colorado), and J. D. Balcomb, Conservation and Solar Guidelines, *8th National Passive Solar Conference*, *Santa Fe* NM 1983, p. 117.
9. J. D. Balcomb, R. D. Mcfarland and W. O. Wray, *Passive Solar Heating Analysis, a Design Manual*, ASHRAE (1984).
10. J. D. Balcomb, R. D. McFarland and S. W. Moore, Passive Testing at Los Alamos, *Proceedings of the Second National Passive Solar Conference*, Philadelphia (1978), pp. 602–609.
11. J. D. Balcomb, R. D. McFarland and S. W. Moore, Simulation Analysis of Passive Solar Heated Buildings—Comparison with Test Room Results, Proceedings of the American Section of ISES, 1977 Annual Meeting, Orlando, Florida, June 6–19, 1977.
12. J. C. Hyde, Passive Test Cell Experiments During the Winter of 1979–80, Los Alamos National Laboratory report LA-9048-MS (September 1981).
13. R. D. McFarland, Passive Test Cell Date for the Solar Laboratory, Winter 1980–81, Los Alamos National Laboratory report LA-9300-MS (May 1982).
14. E. F. Moore and R. D. McFarland, Passive Solar Test Modules, Los Alamos National Laboratory Report (1982).
15. W.O. Wray and C. R. Miles, A Passive Solar Retrofit Study for the United States Navy, Proceedings of the 6th National Passive Solar Conference, Portland, Oregon (8–12 September 1981).
16. J. D. Balcomb, Dynamic Measurement of Heat Loss Coefficients Through Trombe Wall Glazing Systems, *Proceedings of the 6th National Passive Solar Conference, Portland, Oregon* (8–12 September, 1981).
17. K. Butti and J. K. Perlin, *A Golden Thread*—2500 *years of solar architecture and technology*, Cheshire Books, p. 207 (1980).
18. J. Hyde, Performance of Night Insulation and Selective Absorber Coatings in LASL Test Cells, *5th National Passive Solar Conference, Kansas City*, MS, p. 277 (1980).
19. Arume Noe, Field Validation of the DEROB PASOLE System *3rd National Passive Solar Conference, San Jose*, p. 152 (1979).

20. Part of a continuing series of simulation model intercomparisons and comparisons with measured data, underway at the Polytechnic of Central London.
21. APACHE is a large finite difference simulation code including detailed treatment of plant, available commercially from Facet UK.
22. G. Kawahji, P. Burns and B. Winn, Convective Studies in the Sunspace of the REPEAT facility, ASME Paper 90, 85-WA/Sol-12 (1985).
23. D. D. Weber, W. O. Wray and J. Kearney, LASL Similarity Studies II, Similitude Modelling of Interzone Heat Transfer by Natural Convection, *4th National Passive Solar Conference*, p. 231 (1979).
24. F. Bauman, A. Gadgel, R. Kammerud and R. Greif, Buoyancy Driven Convection in a Rectangular Enclosure, Lawrence Berkeley Labs. Report 10257, 1980. From LBL Berkeley CA 94720 (1980).
25. P. Linden and J. Simpson, Buoyancy Driven Flow Through an Open Door, AIR 6, p. 4 (1985).
26. R. Anderson, in the SERI House Journal Science and Technology in Review, 1990, from SERI, 1617 Cole Bld, Golden, CO 80401 (1990).
27. Personal communication from Dr Detzer of Kessler and Luch, Giessen, Germany.
28. J. D. Balcomb and K. Yamaguchi, Heat Distribution by Natural Convection, *8th Passive National Passive Conference, Santa Fe*, p. 289 (1983).
29. J. Klems, S. Selkowitz and D. Horowitz, A Mobile Facility for Measuring Net Energy Performance of Windows and Skylights, 3rd International Symposium on Energy Conservation in the Built Environment, Dublin (1981).
30. M. McCabe and D. Hill, Field Measurement of Thermal and Solar/Optical Properties of Insulating Glass Windows, *ASHRAE Transactions* **93**, Pt 1 (1987).
31. The PASSYS Test Cells, Commission for the European Communities Directorate General 12, published by BBRI Brussels, D/1990/0611/10 and the PASSYS Newsletters available from the Belgian Building Research Institute Brussels (1990).
32. WINDOW is public domain software, available from the Windows and Daylighting Group, Lawrence Berkeley Laboratories, Berkeley, California, developed by D. Arasteh, S. Selkowitz and coworkers.
33. P. Robinson and J. Littler, Methodology of Window Thermal Assessment Techniques in the US and UK, Report to the U.K. D. Energy via ETSU (1988).
34. H. Sullivan and J. Wright, Recent Improvements to, and Sensitivity of, VISION, the Glazing System Thermal Analysis Program, 12th National Passive Conference, Oregon (1987).
35. R. McCluney, The Death of the Shading Coefficient, *ASHRAE Journal* p. 36 (March 1991).
36. Annexe 4 of the IEA Energy Conservation in Buildings & Community Systems Programme, Glasgow Commercial Building Monitoring. A quote from one participant noted in Appendix 1 of the Report by members of the SERC-BRE Investigation into Analytical and Empirical Validation Techniques for Dynamic Thermal Models of Buildings, by Bowman and Lomas 1987: "the measurements and computational results should be used neither for 'validating' the existing models, nor for establishing any classification of their respective performances". From SERC, PO Box 18, North Star Ave., Swindon, SN2 1ET, Wilts., UK.
37. A. Tindale, Performance of Solar Hybrid Roof Space Collection Systems. PhD Thesis, Polytechnic of Central London (1991).
38. P. Robinson, Advanced Glazing for Passive Solar Applications: Assessment of Glazing and Whole House Energy Performance by Measurement and Prediction, PhD Thesis, Polytechnic of Central London (1991).