Field Validation of ICF Residential Building Thermal Mass, Air-Tightness and Ground-Coupling: A Whole Building Demonstration

Presentation at Workshop

Thermal Mass and Its Effect on Performance
Part 1: Whole Building Energy

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Buildings Technology Center

Oak Ridge National Laboratory

Insulating Concrete Form Energy Efficiency Study

Conducted by

Department of Energy

Insulating Concrete Form Association

Loudon County Habitat for Humanity

Reward Wall Systems

Portland Cement Association

ORNL Buildings Technology Center

Results from field tests in the Knoxville, TN climate

- How strong is the ground connection? Evidence from temperature sensors embedded in the foundation walls of the side-by-side houses
- How air tight is the ICF house? Comparison of air leakage in houses measured with software-controlled blower door
- What benefits of ICF thermal mass are seen in the Knoxville climate? Results for its humid Summer, its mild Winter and its long Fall and Spring seasons
- How will field test results lead to a simple analytical tool for generalizing the benefits of ICF construction?

Side-by-Side Houses

Insulating Concrete Form (ICF) Construction

Side-by-Side Houses

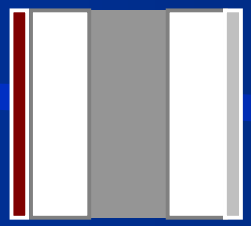
Conventional Wood-Framed (CWF) Construction

Side-by-Side Houses: Comparison of Wall R-values

(All values in h·ft²·°F/Btu)

ICF Construction

Siding



Wallboard

Foam Foam
Concrete

Clear Wall R-17.1

bare wall value measured
without siding + wallboard

Whole Wall R-15.0

reduced for effect
of corners + openings

CWF Construction

Siding

Wallboard

Insulation
or Studs

Clear Wall R-11.1

insulation path R-12.6
stud path R-5.1

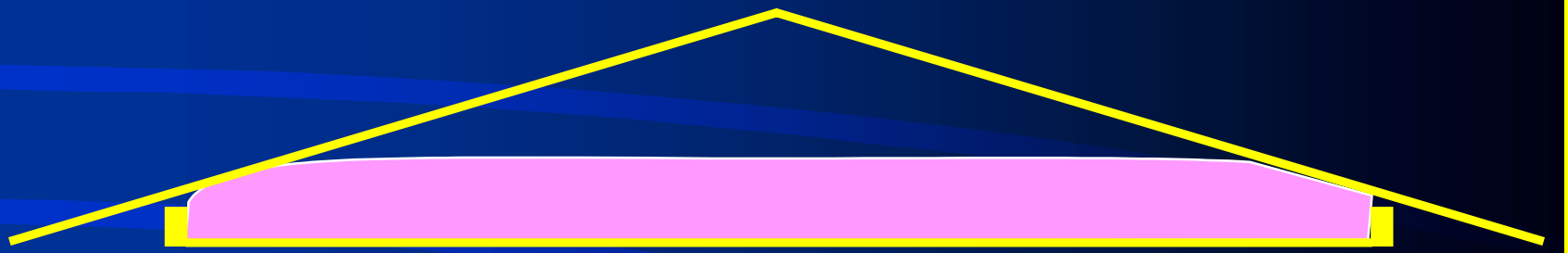
Whole Wall R-10.6

reduced for effect
of additional framing

Side-by-Side Houses: Comparison of Attic R-values

(All values in h·ft²·°F/Btu)

ICF Construction same as CWF Construction



Center of Attic through Insulation: R-32.5

includes roof shingles + roof deck + attic air space + ceiling

Whole Ceiling: R-28.4

reduced for effects of trusses 24 in. oc and for decreased thickness of insulation at eave edges

Side-by-Side Houses: Comparison of Floor R-values

(All values in h·ft²·°F/Btu)

ICF floor hung from the continuous foundation-to-roof external wall

CWF crawlspace concrete masonry unit wall topped by extra wood band joist

Floor through Insulation: R-19.3

carpet + pad + subfloor + R-19 batt (less 10% for penetrations)

Whole Floor: R-17.9

reduced for effects of exposed floor joists 16 in. oc, including extra 2x10s around perimeter

Instrumentation in Side-by-Side Houses

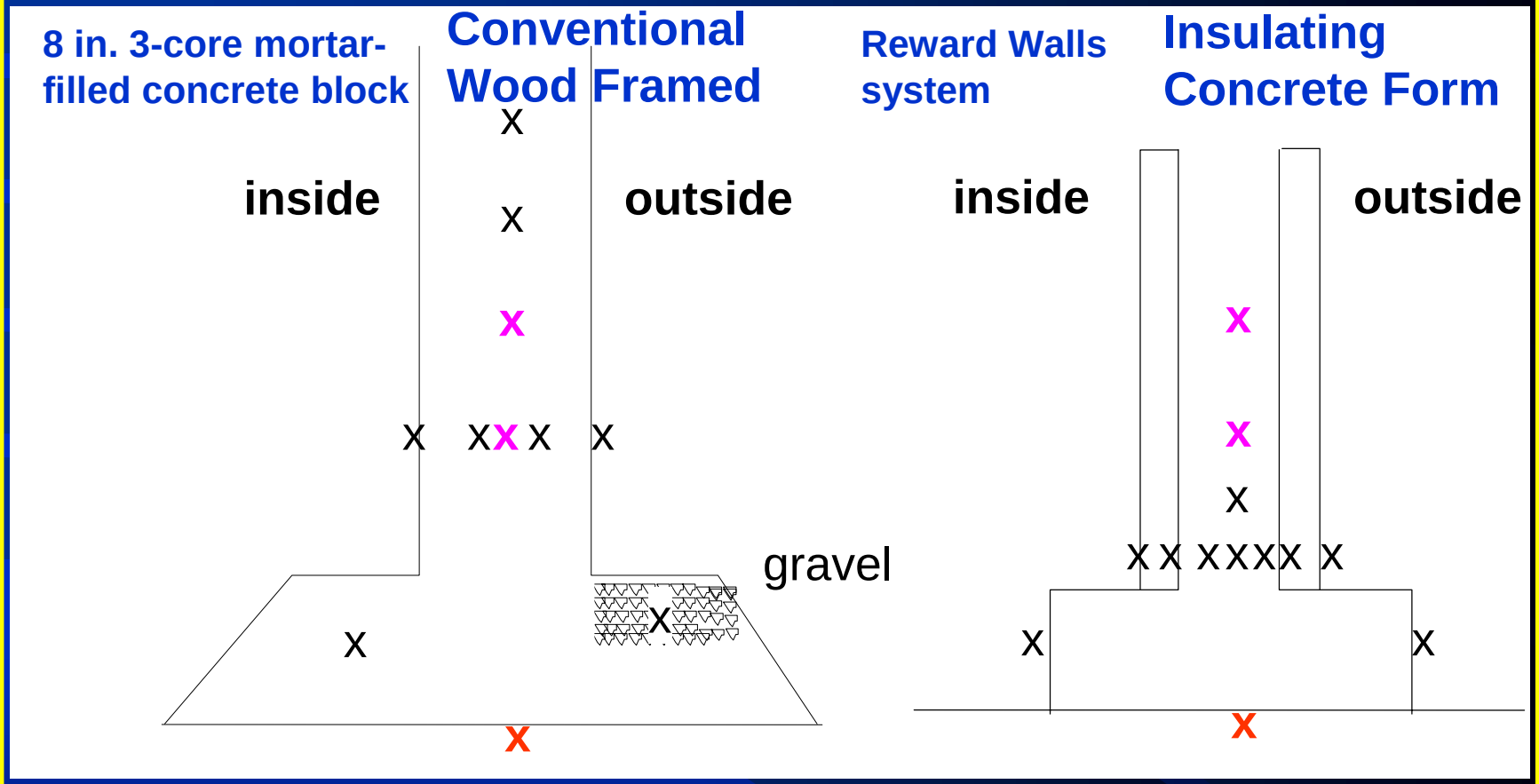
Living spaces, attics and crawlspaces instrumented with thermocouples, heat flux transducers and relative humidity sensors. Electricity use also monitored

Total Channels of Data Acquisition in Each House:

51 Temperatures (total of 90 thermocouple measuring junctions)
4 Heat flux transducers
4 Relative humidity sensors
2 Electrical power transducers on heat pump
1 Whole-house pulse-initiating kilowatt-hour meter

Side-by-Side Houses: Focus on foundation walls

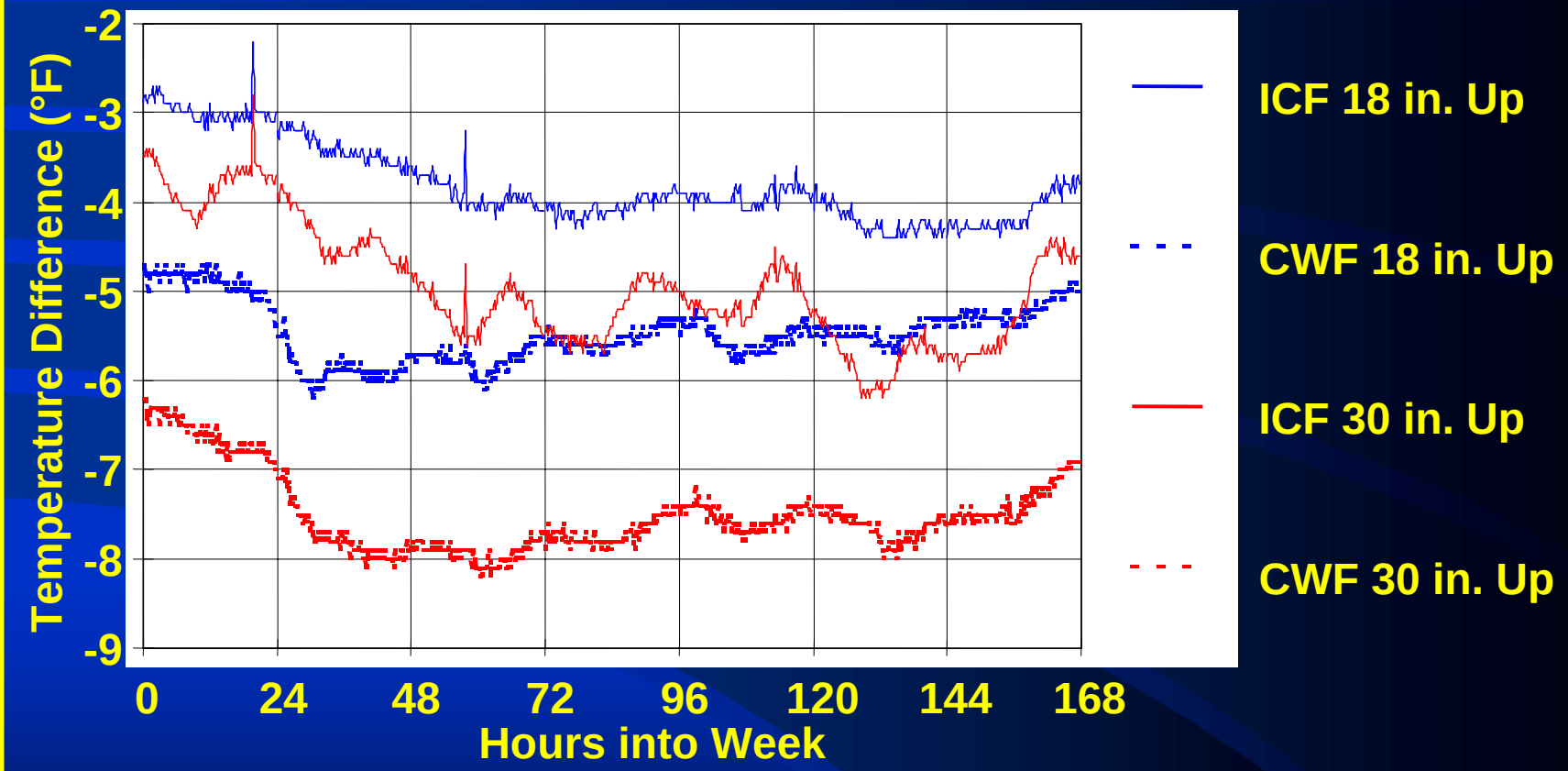
X Locations of Individual Thermocouples for Local Temperatures



Form differences between x centerline temperatures and x footer temperatures for evidence of ground connection

Insulating Concrete Form (ICF) vs Conventional Wood-Framed (CWF) Foundation Walls

Wall - Footer Temperatures 12/29/00 to 1/4/01 (Peak Heating)



Core of ICF wall is 2-3°F warmer than CWF foundation wall. Effect on energy not enough to prevent successful one-dimensional modeling

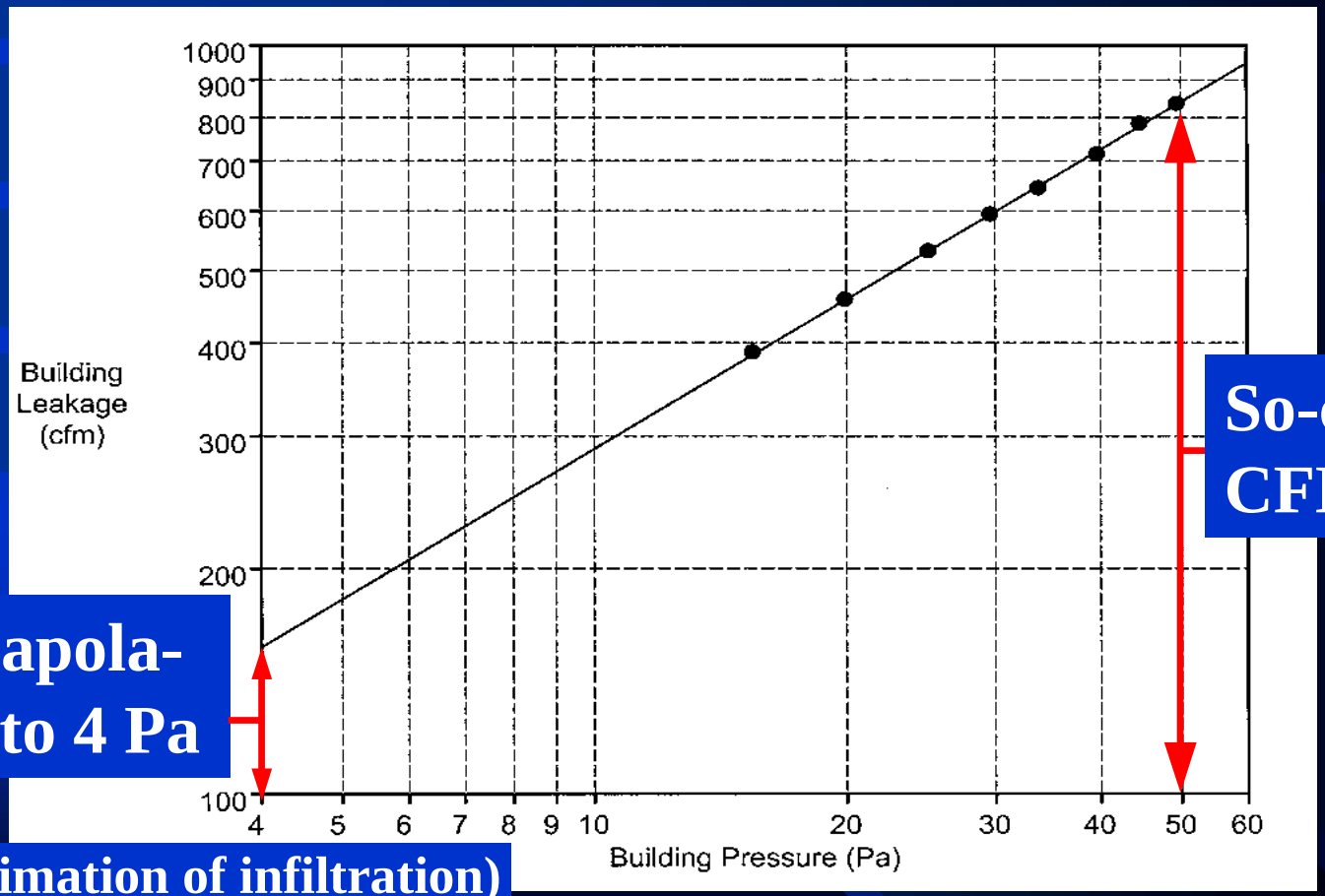
Insulating Concrete Form (ICF) vs Conventional Wood- Framed (CWF) House Blower Door Tests

Tests done with state-of-the-art software-controlled blower door

System adjusts speed of the fan and monitors building pressure and fan air flow rate to produce points on leakage curve

Insulating Concrete Form (ICF) vs Conventional Wood- Framed (CWF) House Blower Door Tests

State-of-the-art software-controlled blower door produces accurate and reproducible leakage curve

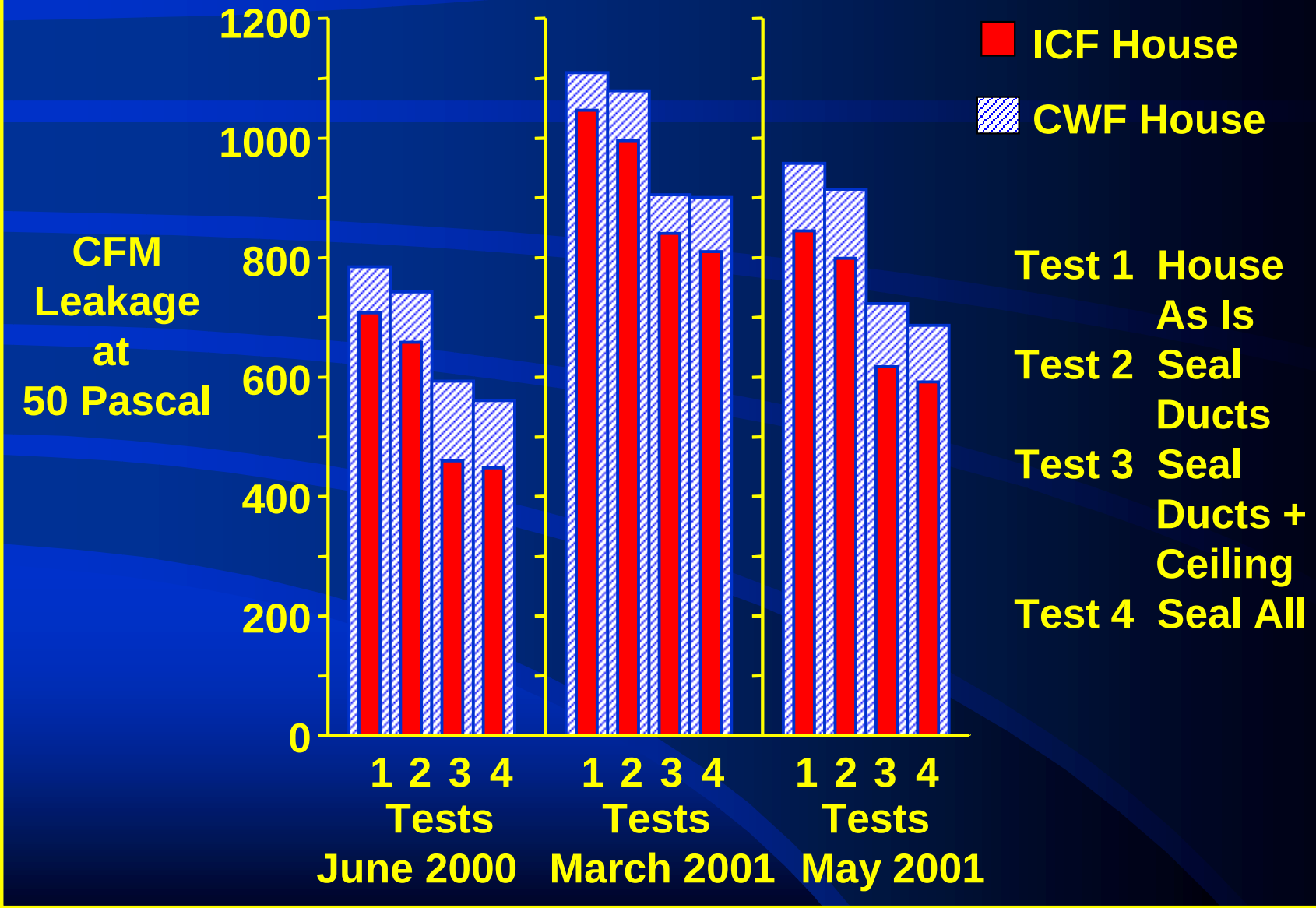


So-called CFM_{50}

Extrapola-tion to 4 Pa

(for estimation of infiltration)

Results of ICF and CWF House Blower Door Tests



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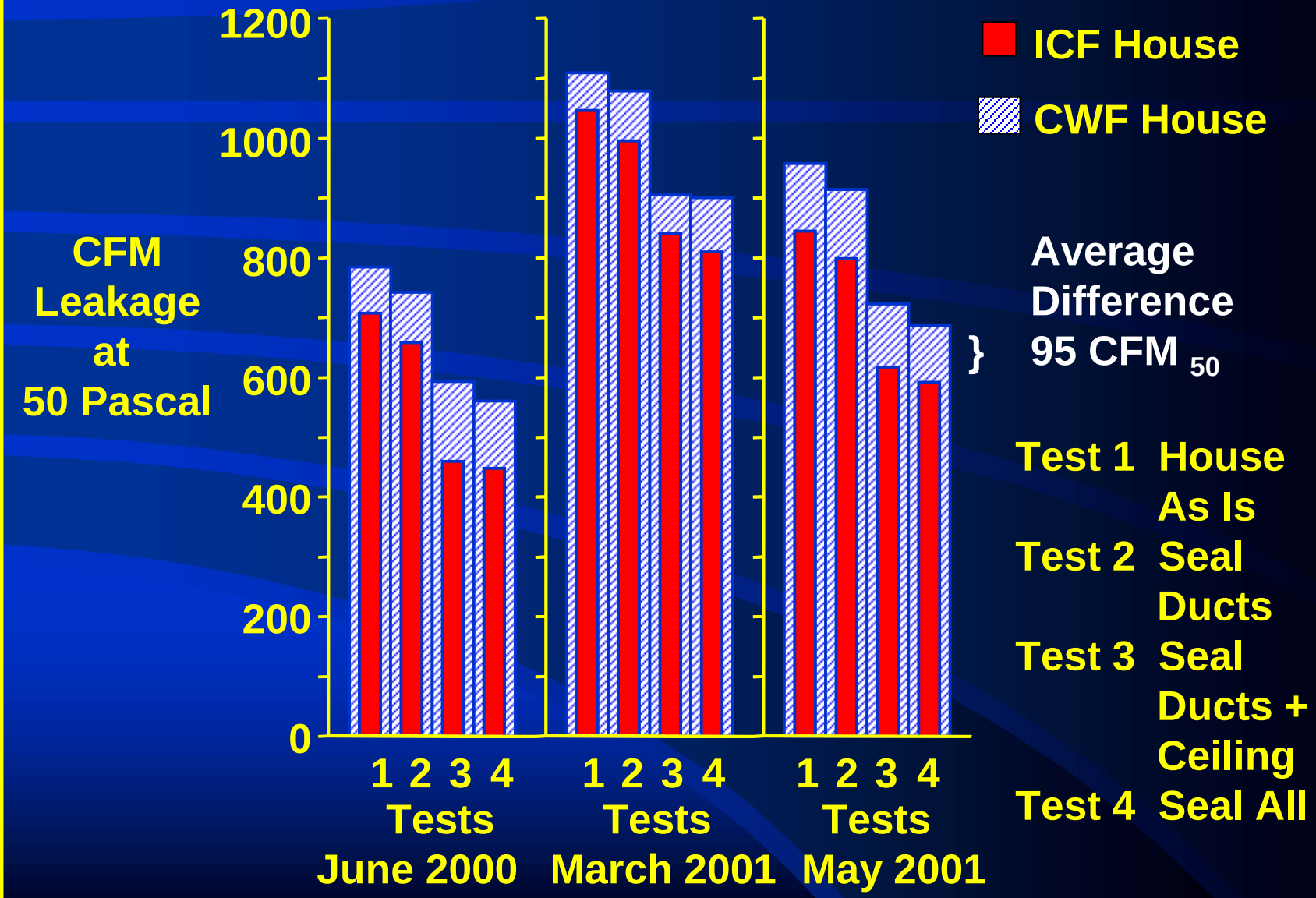

Conclusions from ICF and CWF Blower Door Tests

- **The CWF - ICF difference in leakage is about the same for each test and persists as components are sealed. Conclude that it is primarily due to effects of foundation-exterior wall joint in the CWF house**

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Conclusions from ICF and CWF Blower Door Tests

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- **The average difference of 95 cfm_{50} is not larger than the ±10% uncertainty in results of a few blower door tests.** This experiment does not allow us to say that ICF houses are significantly more air tight than carefully built conventional wood-framed houses
- **Resulting leakage fraction (cfm @ 4Pa / floor area) for winter conditions is 0.00038 for ICF, 0.00042 for CWF.** These values are less than 0.00050, which is anticipated for "average tightness" in wood-framed construction

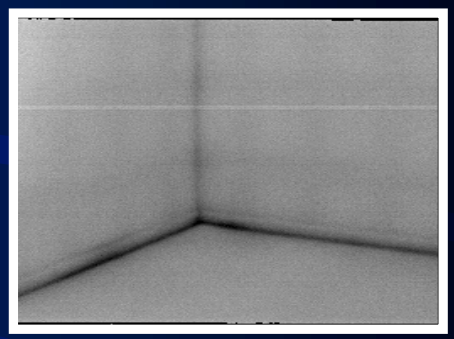
Results of ICF and CWF House Infrared Imaging

Infrared survey done of exteriors and interiors of houses during cold weather. Gave indication of thermal bridges in each house

CWF House Bedroom 3

Black-and-white images show internal structure: studs vs. webbing

ICF House Bedroom 3



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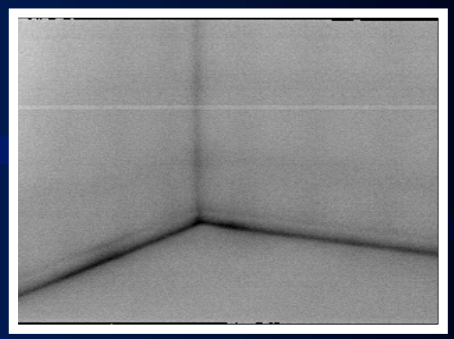
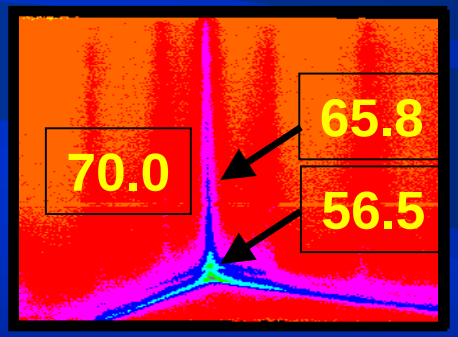
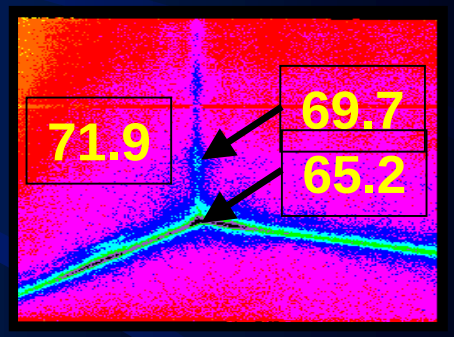




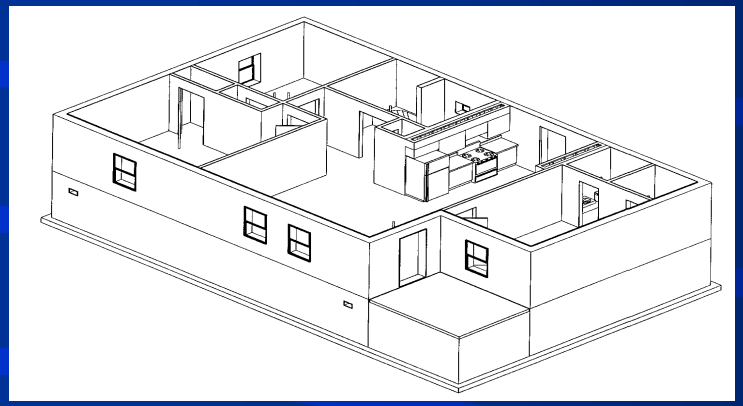
Color images show that CWF's corner is colder than ICF's (color vs. tempera-ture not same on each image)

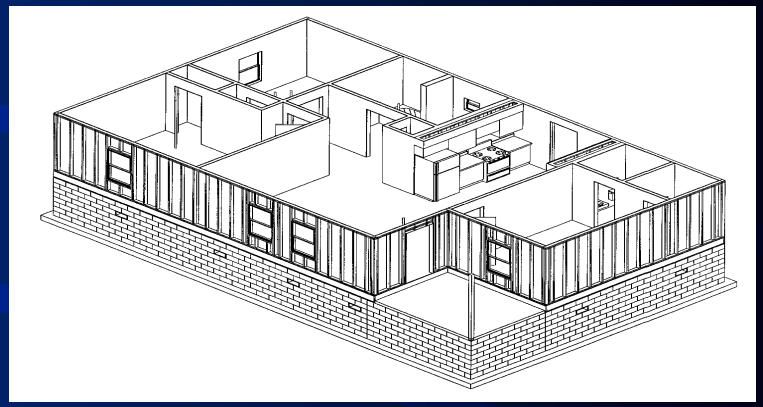


Confirms effect of foundation-exterior wall joint in CWF house that was seen in blower door tests and higher R-value of ICF wall

Cooling / Heating Performance of Whole Houses

Unoccupied houses operated with steady 130 W internal load in each due to monitoring equipment, constant 72°F thermostat setpoints and continuously-on circulation fans





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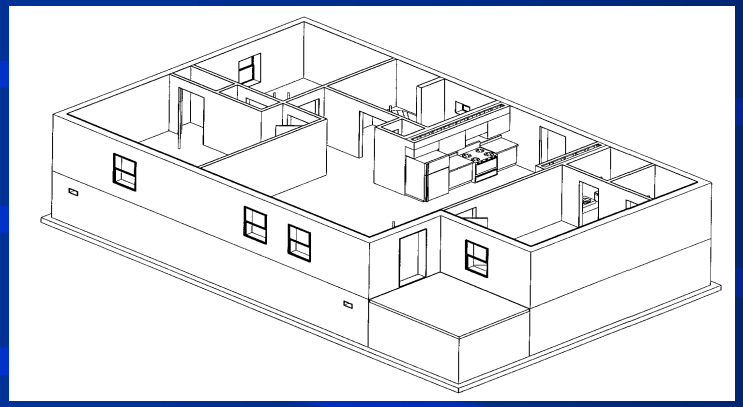
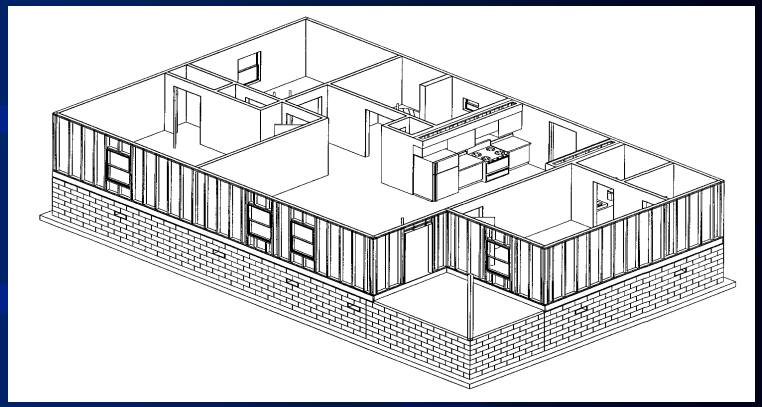


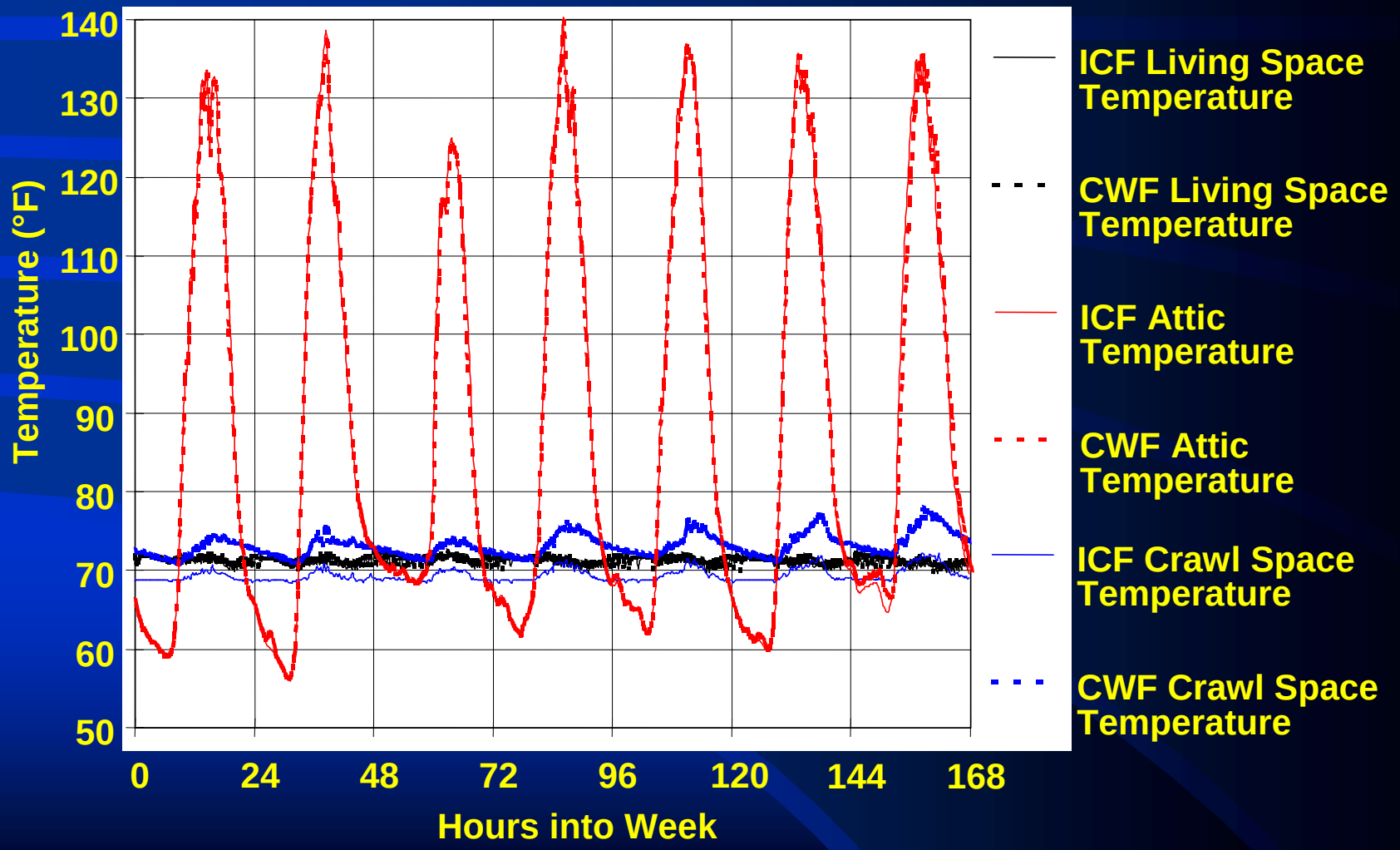


Claims affecting comparison of ICF and CWF houses:

- **Attic temperatures identical. Therefore, R-30 attic insulation in both houses buffers living spaces in the same way from extremes in summer and winter**
- **Due to different vent areas, small crawlspace temperature differences exist. They act through R-19 floor insulation. Correct measured energy of CWF house for small effect.**

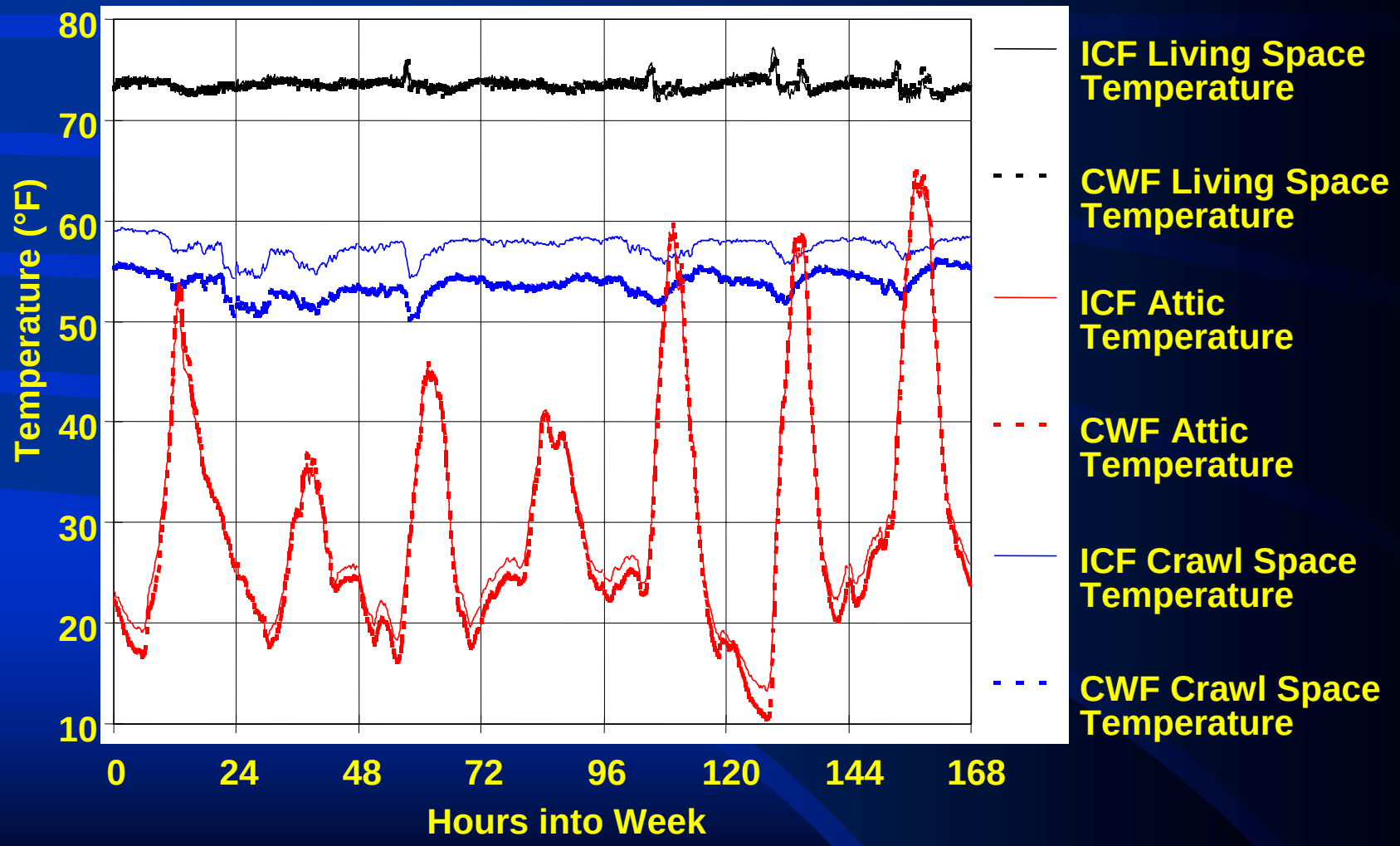
Living Space, Attic and Crawlspace Temperatures

ICF and CWF Temperatures - 08/25 to 08/31/00 (Peak Cooling)

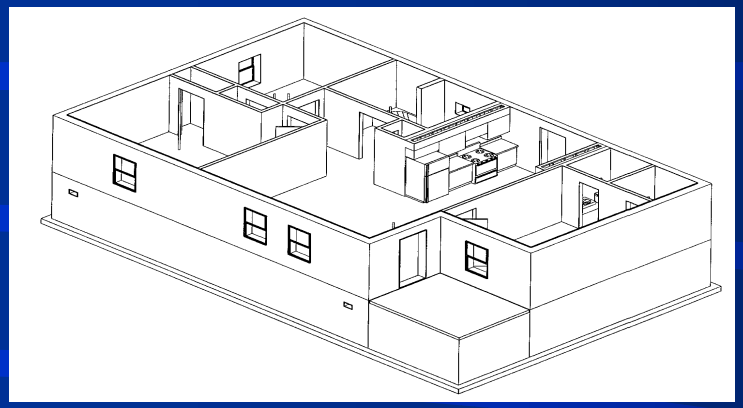


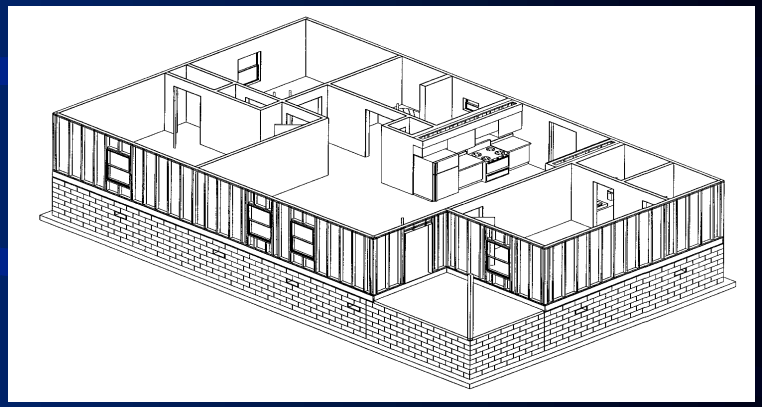
Living Space, Attic and Crawlspace Temperatures

ICF and CWF Temperatures - 12/29/00 to 1/4/01 (Peak Heating)



Cooling / Heating Performance of Whole Houses: Measured vs Modeled Total Electricity Use





Claim: Performance differences between ICF and CWF houses due primarily to differences in exterior walls

- **Infiltration difference due to lack of foundation-exterior wall joint in the ICF house carries through to energy performance. Modeled leakage fraction handles difference**
- **Tight (7% air loss) ducts in both houses interact little with crawlspaces. Model handles air leakage into crawlspaces**

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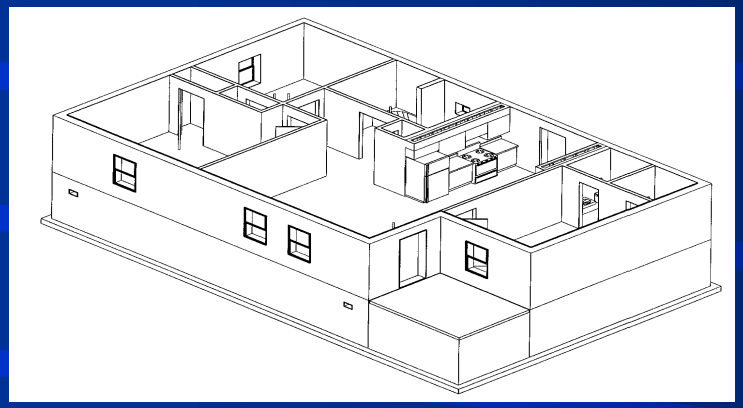

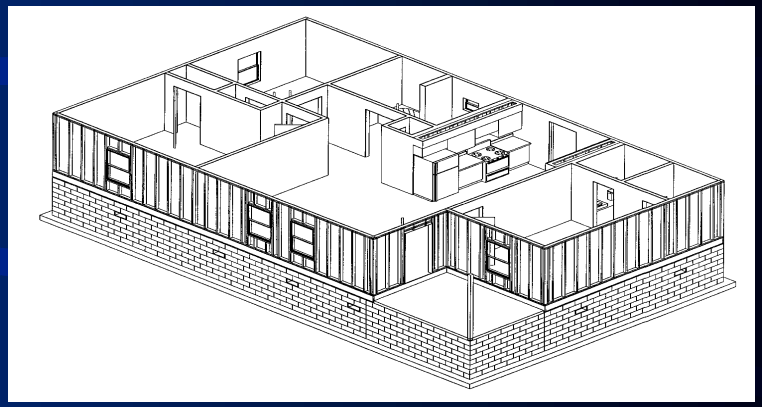

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Modeling essential to gaining insight into differences

From Side-by-Side Tests to Generalized Comparisons

- Pulse-initiating kilowatt-hour meters for total energy use and submeters on heat pumps provide detailed data
- Make detailed comparisons of house models and field test data during peak months of cooling and heating seasons
- Use to validate models of side-by-side houses
- Exercise validated models for additional house features and a variety of climates that will elucidate the advantages of ICF over CWF construction
- Generalize results of comparisons into form that can be used independently of models (such as a web-based calculator)

To date, have made validated models of side-by-side houses and added features for typical occupancy and schedules

Measured vs Modeled Energy Use for Whole Houses

Detailed comparison of measured vs modeled total electricity use is shown for 4 weeks of cooling with electric air conditioning and 4 weeks of heating with electrical resistance heaters. Meteorological data from Oak Ridge NOAA and ORNL weather stations were used in the DOE2.1E energy use program

Conventional House (kWh)

	Measure	Predict
Cooling	559	536
Heating	2566	2570

ICF House (kWh)

	Measure	Predict
Cooling	528	530
Heating	2343	2323

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Conventional House (kWh)

	Measure	Predict	% Difference
Cooling	559	536	-4.1
Heating	2566	2570	+0.2

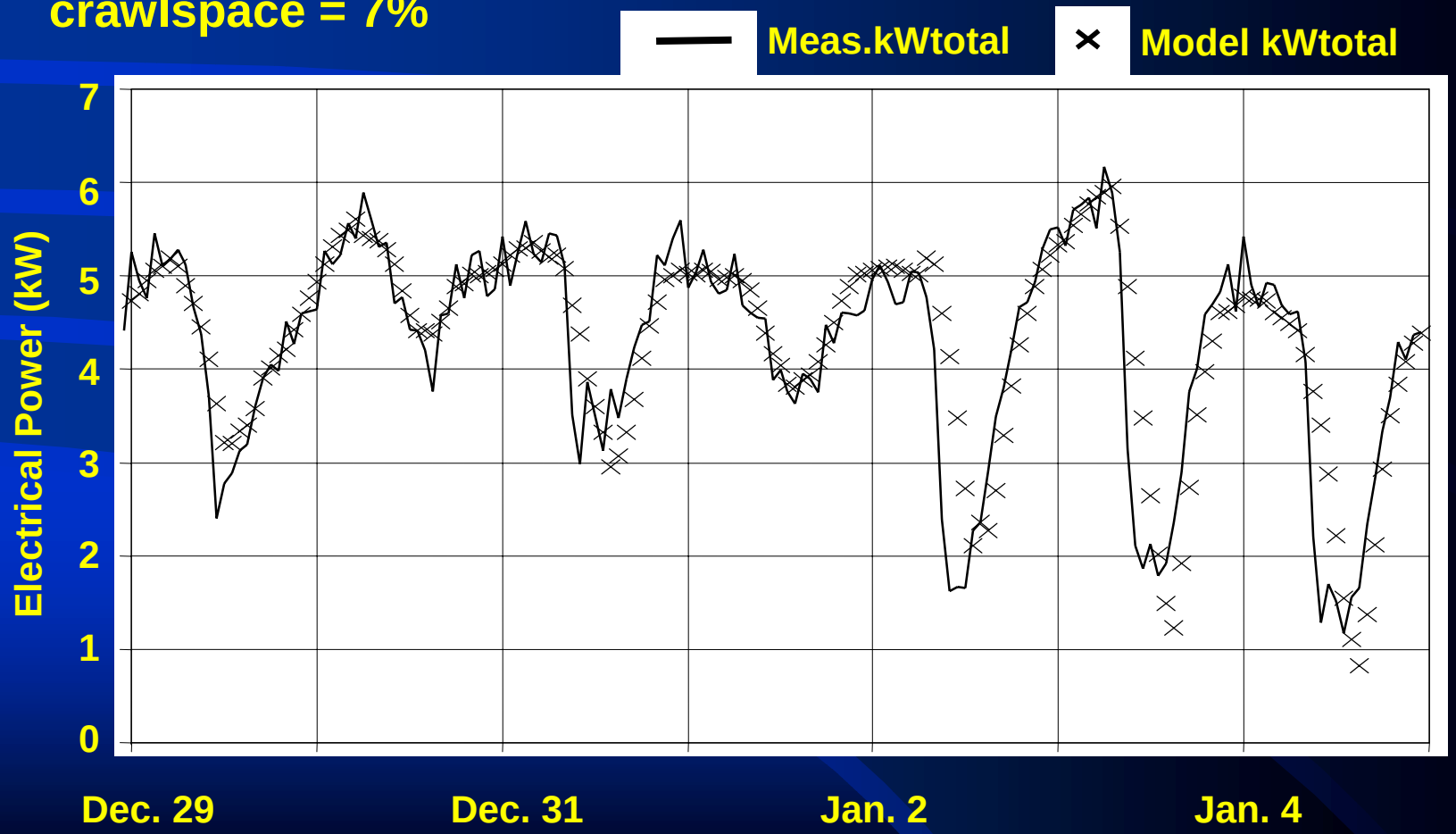
ICF House (kWh)

	Measure	Predict	% Difference
Cooling	528	530	+0.4
Heating	2343	2323	-0.9

% Difference = (Predict - Measure)/Measure ·100 shows success to ±5%, excellent for DOE2.1E

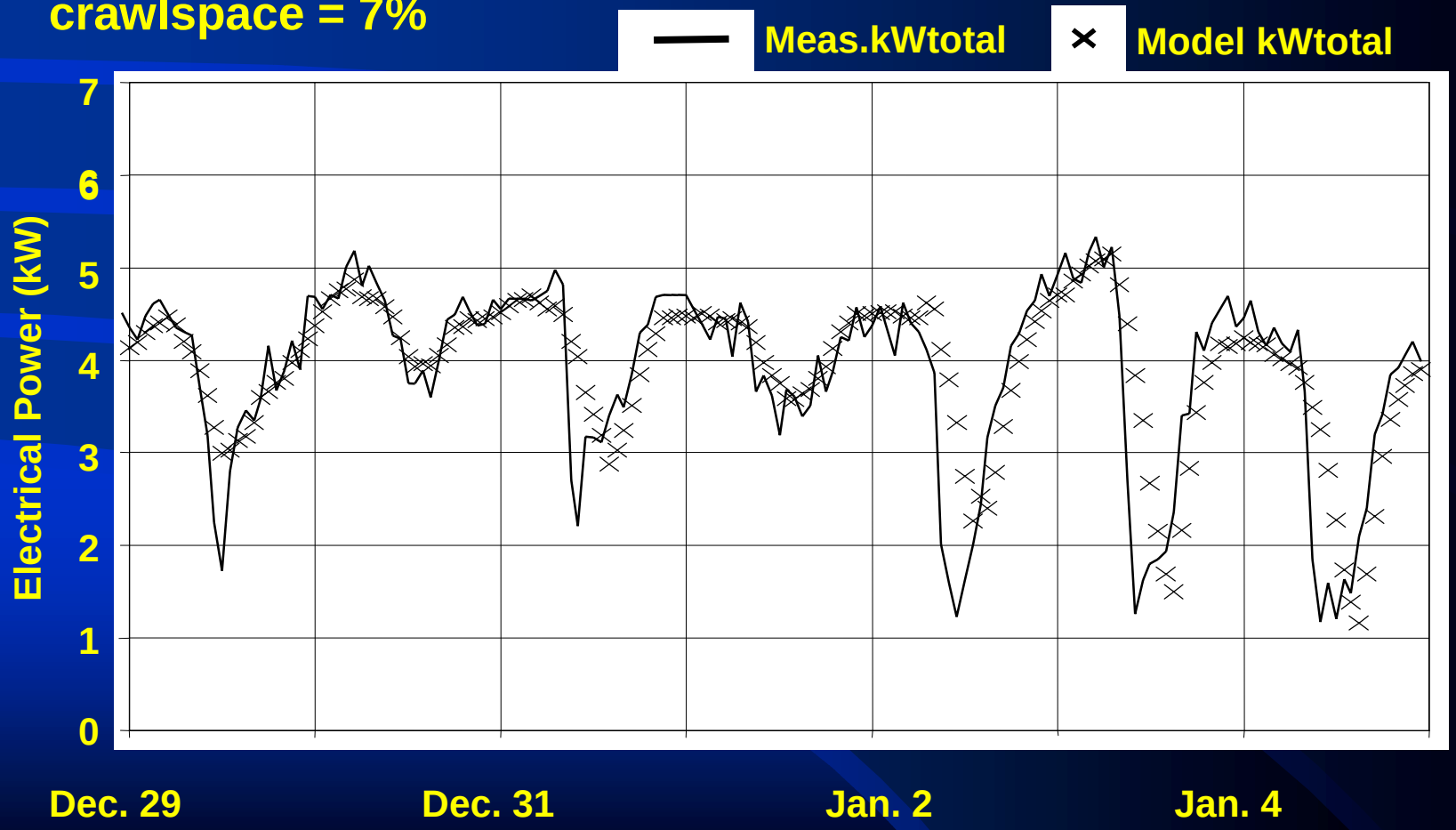
Measured vs Modeled Heating Power Use: Peak Week

Conventional House: Air Leakage Fraction = 0.00042; Exterior whole-wall R-value = 10.6 h·ft²·°F/Btu; R-11 batts between 2x4 studs 16 in. oc; ½ in. OSB external sheathing; Duct air loss to crawlspace = 7%



Measured vs Modeled Heating Power Use: Peak Week

Insulating Concrete Form House: Air Leakage Fraction = 0.00038; Exterior whole-wall R-value = 15.0 h·ft²·°F/Btu; 3.0 in. concrete formed with 2.5 in. foam insulation; Duct air loss to crawlspace = 7%



Generalization for Knoxville TMY2 Annual Weather
More realistic operation + occupancy. All energy in kWh

Features of Occupancy and Operation	No People .14kW Load Strip Heat Cont. Fan Heating 72° Cooling 72°	No People .14kW Load Heat Pump Inter. Fan Heating 68° Cooling 78°
ICF cool	1446	482
ICF heat	6769 kWh_e	3638 kWh_e
ICF total	10035	5577
CWF cool	1489	606
CWF heat	7465 kWh_e	3947 kWh_e
CWF total	10772	6027
%ICF savings	6.8%	7.5%
	As tested	Better operation

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ICF heat	6769 kWh_e	3638 kWh_e	3604 kWh_g
ICF total	10035	5577	11714
CWF cool	1489	606	1214
CWF heat	7465 kWh_e	3947 kWh_e	4688 kWh_g
CWF total	10772	6027	12901
%ICF savings	6.8%	7.5%	9.2%
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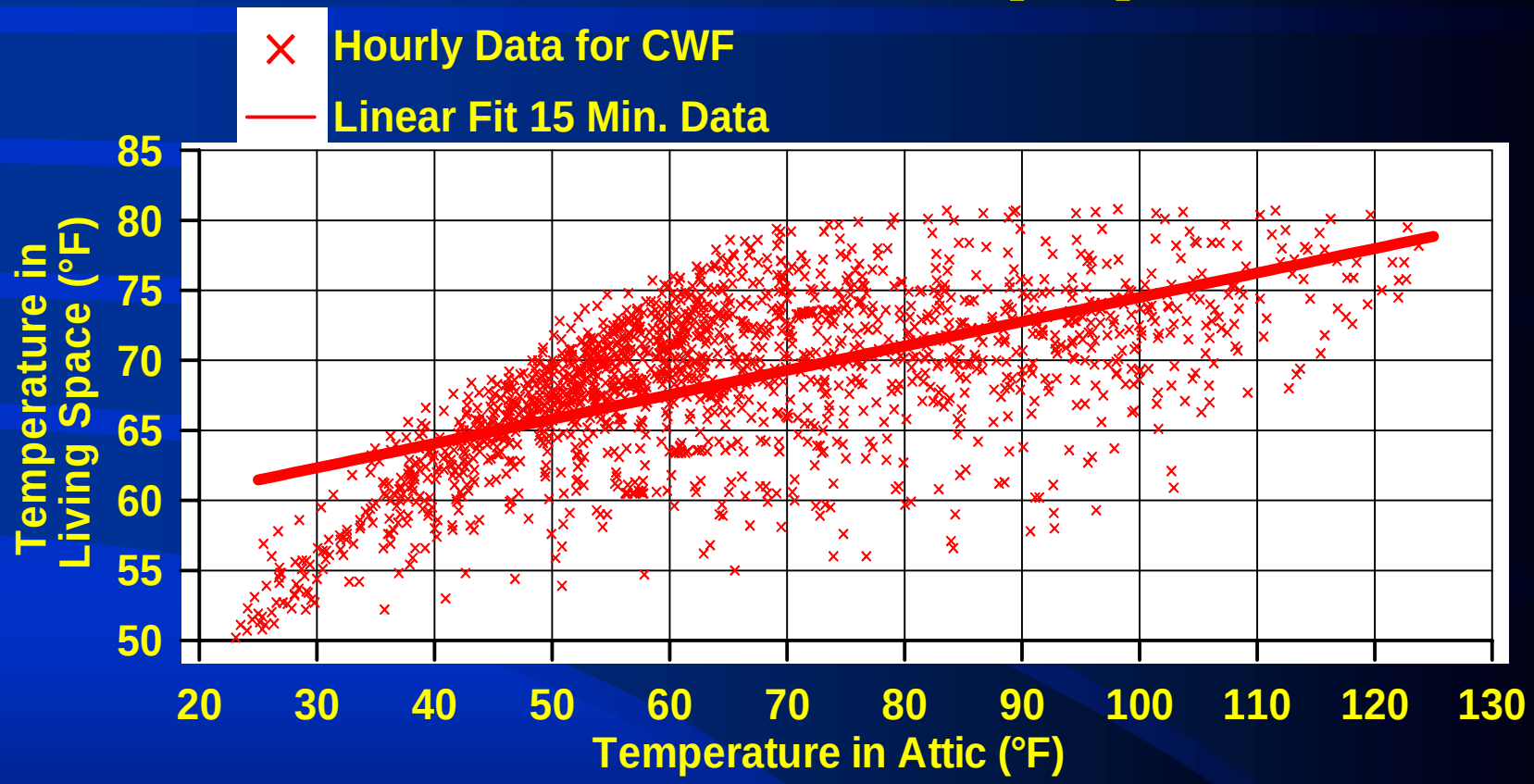
Realistic occupancy+operation brings higher %ICF savings

Swing Season Performance of Whole Houses

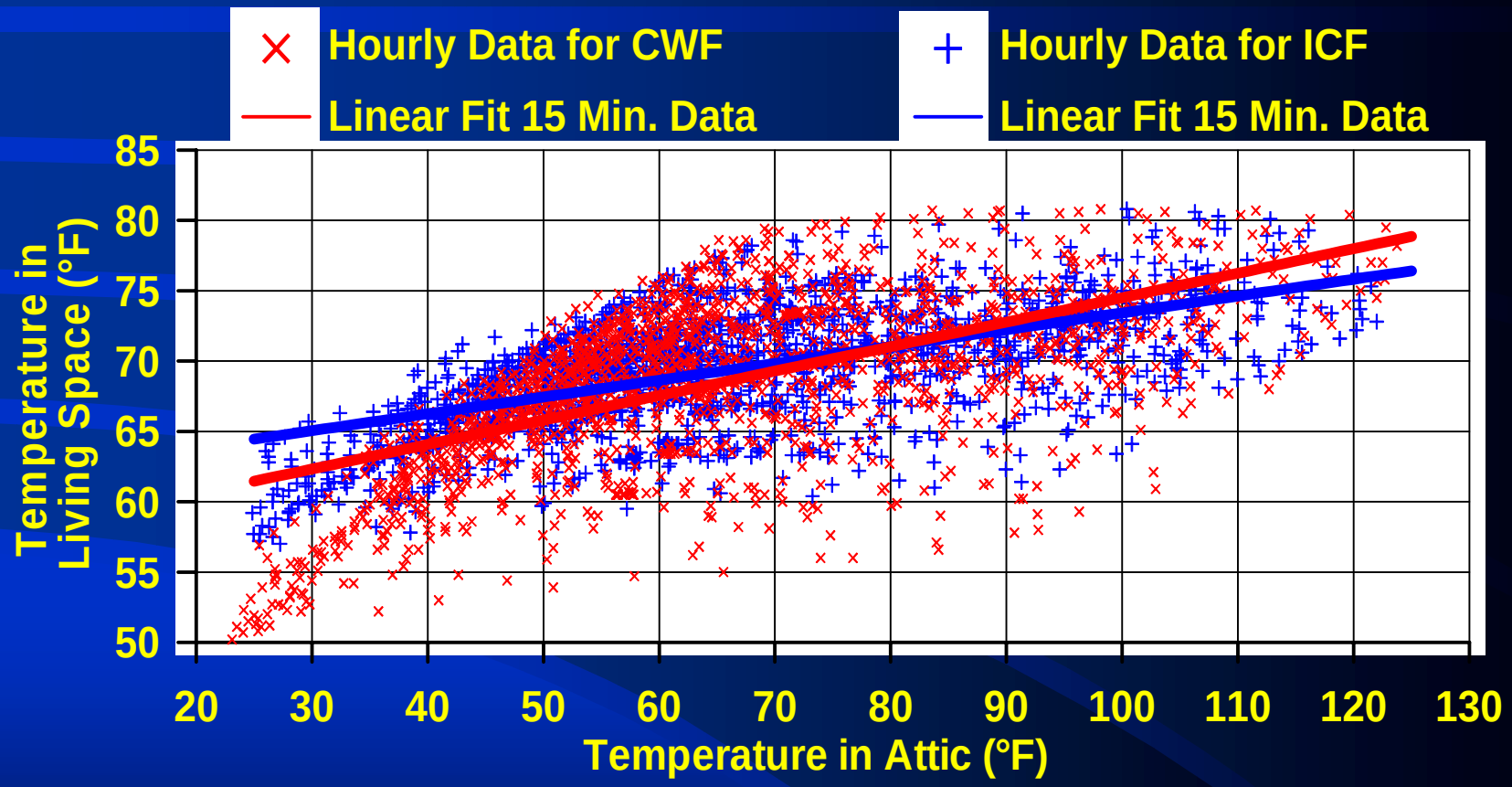
Between cooling and heating seasons, temperatures in both houses were allowed to float with the heat pumps turned off



No energy was consumed for cooling or heating. Use living space temperature to show potential for energy savings

Swing Season Performance of Whole Houses

Living space vs attic temperatures show that the ICF house has narrower temperature swings than the CWF house



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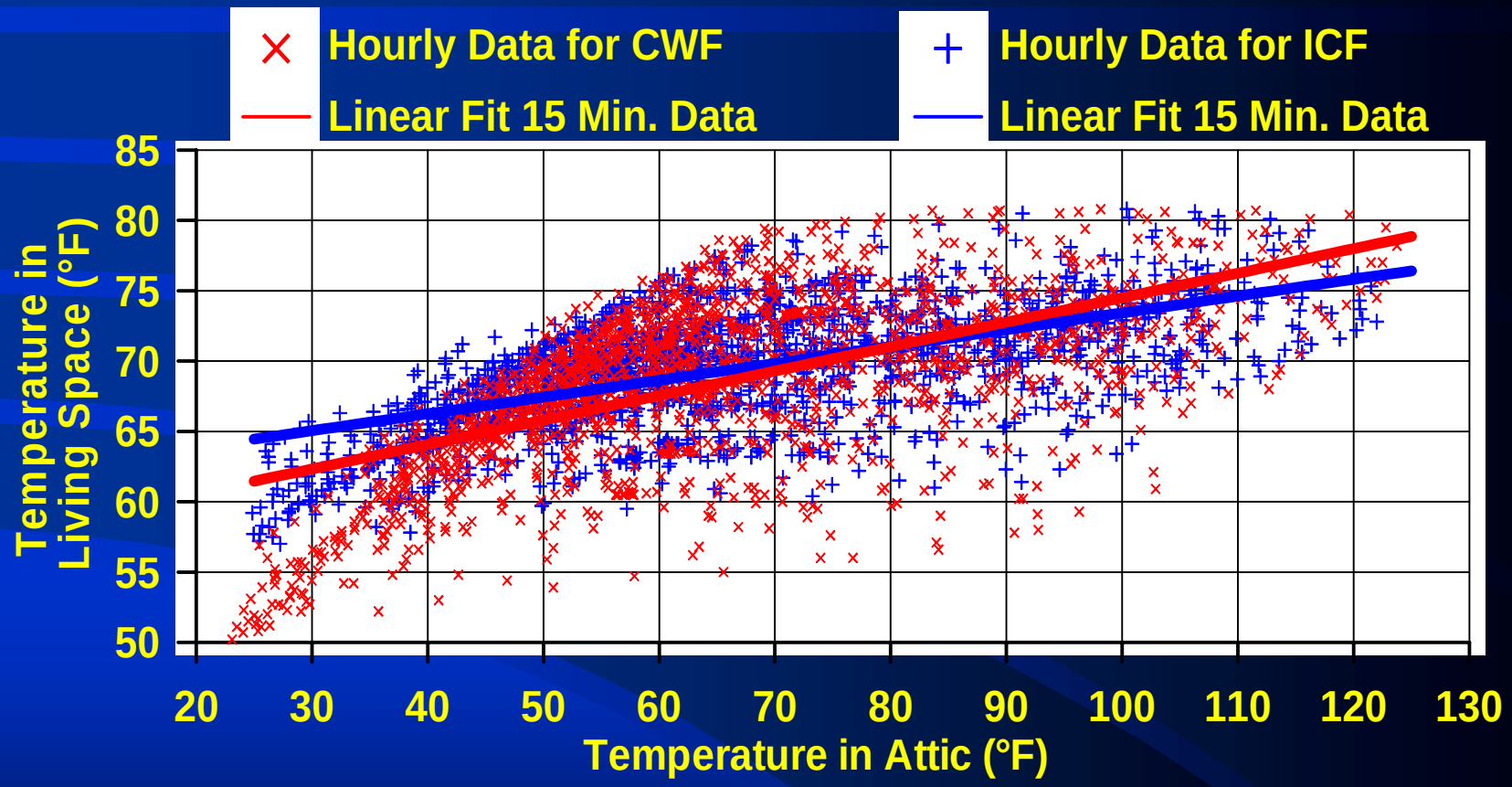

If houses were occupied, claim cooling / heating would not be used as often in the ICF house to keep conditions "livable"

Swing Season Performance of Whole Houses

- In East Tennessee, due to the mild Spring and mild Fall weather, residential HVAC systems can be operated occasionally for at least 15 weeks during these swing seasons
- Homeowners make individual decisions about when to start and stop their HVAC systems. The decisions are based on perceptions of thermal comfort and tolerance to high and low temperatures
- The main factor affecting the decisions is daily fluctuation of temperatures in the house. Another important factor is the daily work, school, … schedules of the occupants

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Illustrate possible energy savings by an example

Swing Season Performance of Whole Houses

One Example of Possible Energy Savings:

- **Assume that the occupants tolerate house air temperature variations between 62°F and 77°F without turning on heating or cooling**
- **From the data for the side-by-side houses without heating or cooling, during the 15 week East Tennessee swing season, very seldom outside range from 62°F to 77°F**
- **Count hours above and below. Convert to days in 15 wks**

Energy Saving Operation during Swing Season

	ICF	CWF
Minimal Days of Cooling	3	6
Minimal Days of Heating	4	15

Swing Season Performance of Whole Houses

One Example of Possible Energy Savings, continued:

- **DOE2 can generate detailed data for any time period. Assume normal operation is 68°F heat (10 pm to 6 am setback to 60°), 78°F cool (10 pm to 6 am setup to 85°F)**

Normal Operation during Swing Season

	ICF		CWF	
	Heating	Cooling	Heating	Cooling
Total normal kWh	328		542	
Days of Significant Use	20	27	28	30
Average kWh/DofS Use	6.6	4.9	11.3	5.0

Swing Season Performance of Whole Houses

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Minimal vs Normal Operation during Swing Season

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Days of Significant Use	20	27	28	30
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Days of Minimal Use	4	3	15	6
Minimal kWh	26	15	169	30

Swing Season Performance of Whole Houses

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Days of Significant Use	20	27	28	30
Average kWh/DofS Use	6.6	4.9	11.3	5.0
Days of Minimal Use	4	3	15	6
Minimal kWh	26	15	169	30
Savings vs Normal	287		343	
Annual Use (ICF saves 9.0%)	11427		12558	

Conclusions from Side-by-Side Tests

- Connection between ground and exterior walls in Insulating Concrete Form (ICF) house not strong enough to prevent good agreement between measurements and one-dimensional DOE2 model
- Blower door tests show that ICF house is about 10% more air-tight than side-by-side conventional wood-framed (CWF) house
- Air leakage in side-by-side houses was less than anticipated based on literature values for conventional construction

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- Same construction features but more realistic occupancy and operation in Knoxville show 9.2% annual energy savings by ICF vs 12900 kWh in CWF house
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Insulating Concrete Form Energy Efficiency Study

Conducted by

Department of Energy

Insulating Concrete Form Association

Loudon County Habitat for Humanity

Reward Wall Systems

Portland Cement Association

ORNL Buildings Technology Center