

Solar Hop & Herb Drying Greenhouse System: Using Hot Air Collectors for Small Scale Growers

Richard Andrews, President
Boulder Innovative Technologies, Inc.
and J. M. Andrews Family Farm LLLP
Boulder, CO February 2013 Update

Andrews Family Farm

Veg/Fruit CSA, Hop and Herb Farm

- 6+ acre organic farm in Boulder County, Colorado
- 1+ acre in hops, low trellis (13 ft)
 - Cascade, Chinook, Centennial (planted 2008)
 - Experimental yard with seven varieties (2007)
- 1.5 acre in vegetables, operated as working share CSA serving about 50 households
- Medicinal herbs for local herb companies & CSA
- Research for specialty crop & fertilizer research
- Serving other local hop & herb growers with machine picking and solar drying

Andrews Farm in action ---



**Pickin' chard, by kids
and Moms**



**And more pickin'
Bluegrass style**

Ho-Ho-Hoe!



**Out, out *@#!
Mallow out.....**



**The bountious &
luscious rewards....**

More veggies....



More fruits...



**More honey and thanks to
our friendly pollinators....**



**It's
hops
time !!**

And hops pickin' time (home made)!!



***Fresh hops pick up and air freight
delivery to local craft breweries !!***





**Just in time: fresh,
fresh hops for**

Mo-Mentus Ale
10.3% abv
at

Bootstrap Brewing
Niwot, Colorado

**(Dave Mentus
Head brewer)**

Colorado State University

Specialty Crops Program–

Grower Research & Education Grant (GREG)

- 3 year cost shared project to investigate solar drying of hops and herb crops
 - Andrews Family Farm and Hopyard, lead investigator
 - Boulder Innovative Technologies, Inc., cost share-tech support
 - Multiple Colorado hop grower cooperators (Rising Sun Farm, Still Wind Farm, Sabio Creek Farm, Niwot Hops)
- Objective: To build and test solar hot air drying systems suitable for small scale hop and herb growers
- Objective: Outreach and technology transfer to support advancement of high quality hop & herb products, with low fossil energy use, low cost hop processing

Project Activities: Hop Processing Barn & Solar Hop Drying Attached Greenhouse

Current status – greenhouse hot air collection system and hop/herb dryers fully operational

- Barn completion August 2010, first phase solar dryer built
- Photovoltaic 9 kw system installed Fall-Winter 2010
- Solar greenhouse stage I completion July 2011
- Solar Hop hot air dryer operated for harvests of 2011 & 2012
- Solar hot water hop dryer system planned for future system testing 2013-2014 (beyond GREG project)
- **Our intention: to be a totally solar farm with near zero fossil fuel use**

Previous Hop Drying Research

Research in hop drying has been conducted in the early 1950s up through the 1990s. Little has been done since.

Most early work involved conventional fossil fuel fired drying, or traditional oast house systems.

Solar drying was examined in the late 1970s to mid 1980s (USA), Tasmania & India (1979), in the 1990s (Serbia), and most recently in Spain (2009).

Previous Studies and Experiences with Hops and Herb Drying Systems

- **1979 – 1982 Kranzler at Washington State University (solar assisted hop drying, hybrid system with fuel)**
- **1985 Thompson, Stone, Kranzler (Modified Air Flow and Temperature (MAT) hop drying studies; vary velocity and temp during drying for quality and efficiency)**
- **1989 – 1994 Muller, Tesic, and others, (German-Yugoslavian study using a customized greenhouse without supplemental fuel, hops and herb drying)**

Previous Studies and Experience with Hops and Herb Drying Systems

- **Doe, Menary, Bhat (1979), Tasmania & India, Optimization of hop drying for alpha acid content with conventional fuel dryers; solar assist dryer -India.**
- **Mejzr, Hanouser (2007), belt dryer optimization and effect on hop quality, Czech Republic**
- **Henderson, Miller (1958, 1972, 1973, 1974), Univ Calif Davis, equilibrium moisture of hops, drying condition effects on quality; effects of temperature, air velocity**

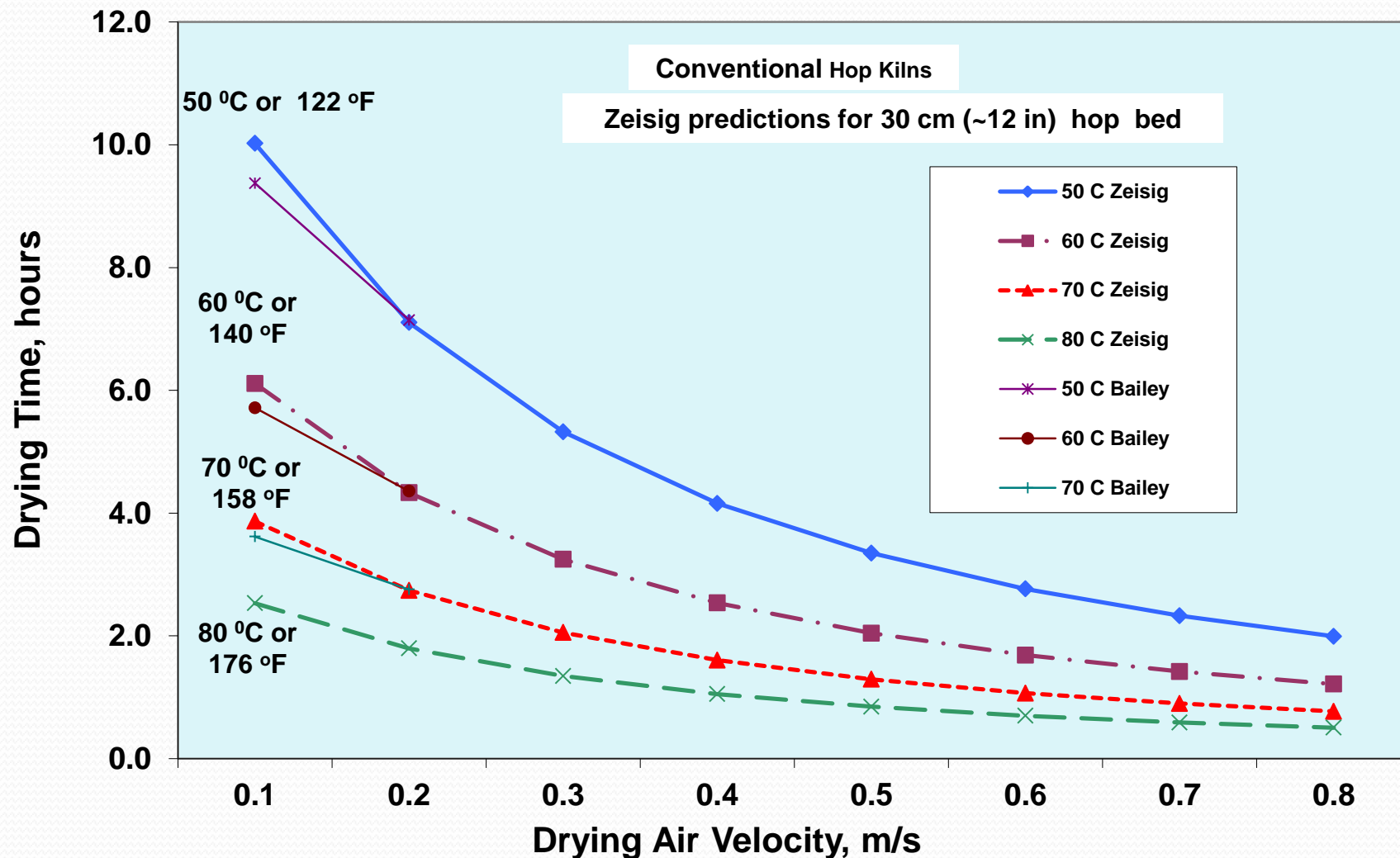
Previous Studies and Experience with Hops and Herb Drying Systems

- **Friedrich, Horder (2006), humidity measuring system for hop drying & conditioning (Germany)**
- **Rossbauer, Munsterer (2009), optimization of hop drying, conditioning & controls for hop quality (Germany)**
- **Abengoza, Moya, Panchos (2009), hot water solar, optimizing hop quality (Spain)**

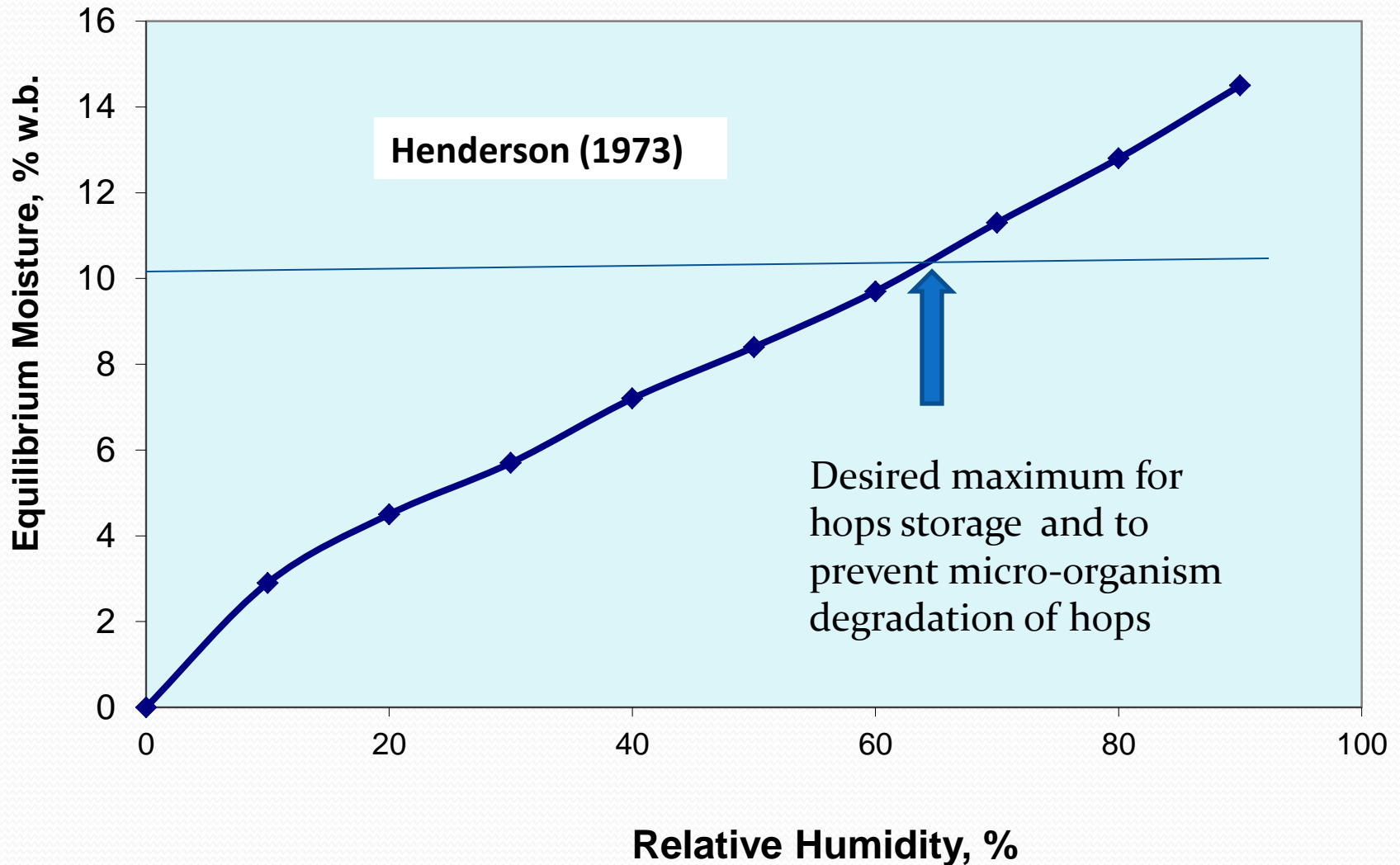
Previous Studies and Experience with Hop Drying Systems

- Bailey, P.H . (1958), J. Agri. Engr. Res. 3(1), 35-46.
Study of effects of temperature and
air velocity on drying duration.**
- Zeisig, H.D. (1970) Proceedings of International Hop
Growers Convention, Brussels, Belgium pp. 131-147
Study of effects of air temperature
and ail velocity on drying duration.**

Hop Drying Times vs. Air Velocity and Temperature



Hops Equilibrium Moisture vs. Relative Humidity



Doe and Menary (1979), Optimization of the Hop Drying Process with Respect to Alpha Acid Content

J. Agric. Engr. Res. 24: 233-248. (Tasmania, Australia)

- measured alpha acid content as affected by temperature, air velocity, and depth of hops in bed
- developed mathematical model of hop drying for conventional multi stage counter-current kiln
- quality affected by temperature and drying duration, but not humidity
- stated peak alpha acid content occurred with drying at 40 °C (105 °F)
- stated overall optimal drying conditions: 0.5 m/s, 69 °C, 0.4 m depth, 6 hr duration

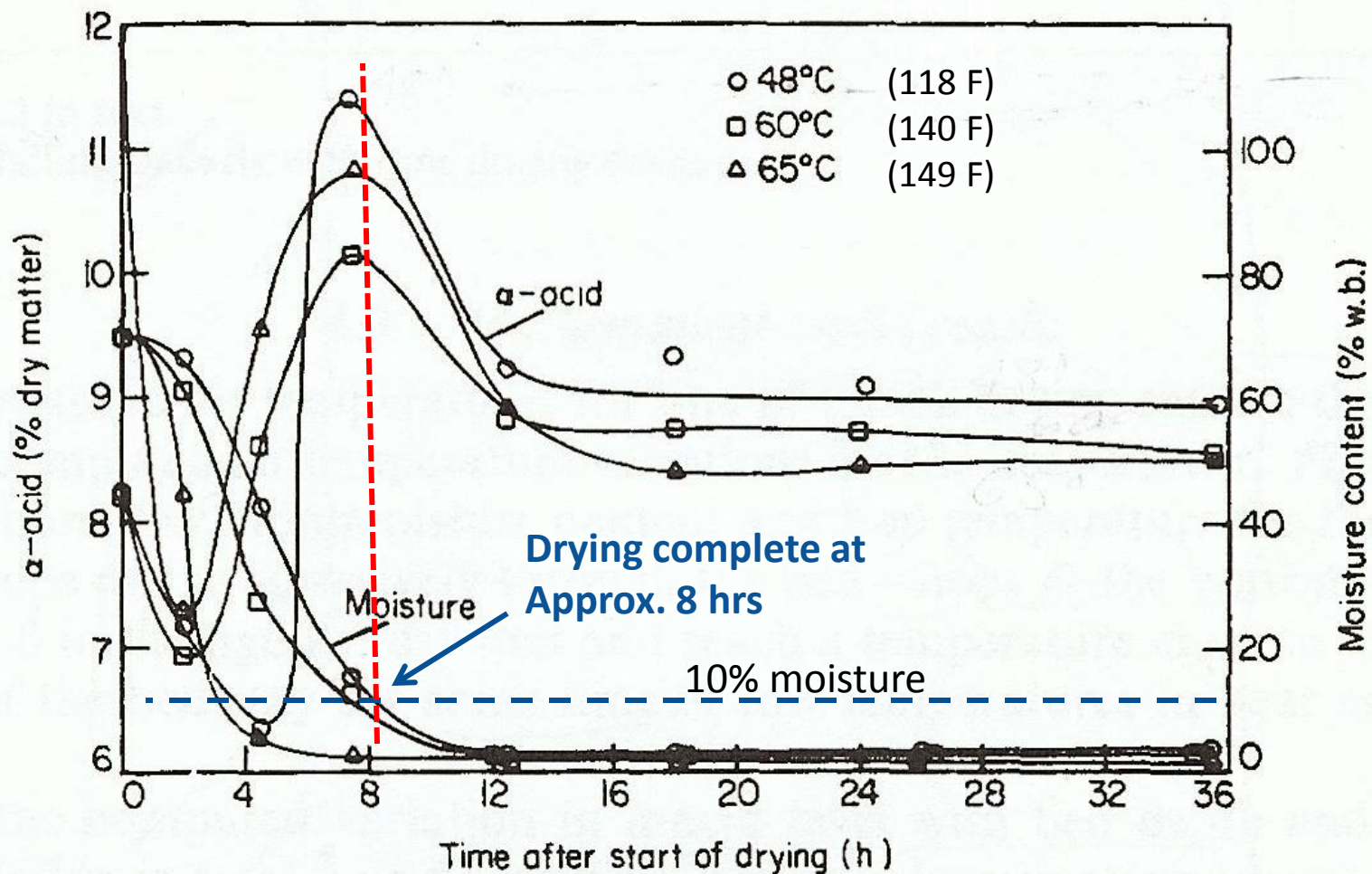
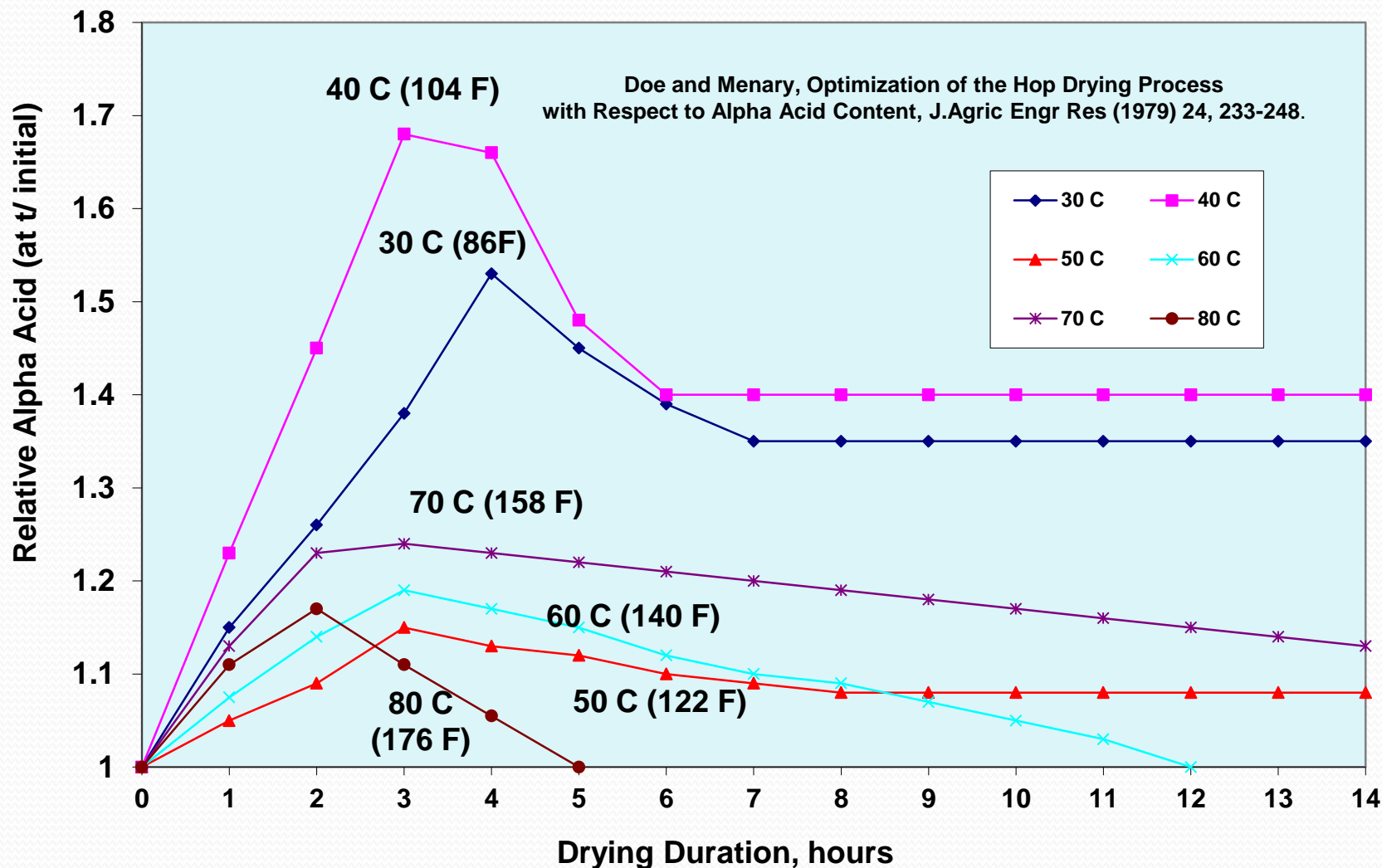


Fig. 7. α -acid-temperature-time characteristics, 1975 harvest

Peak alpha acid at 48 C (118 F), dried in 8 hours

Relative Alpha Acid vs. Drying Time and Temp



Note: Relative alpha is ratio of finished alpha acid divided by initial alpha acid

Conclusions from Doe and Menary (1979) studies in Solar Drying, Tasmania and India

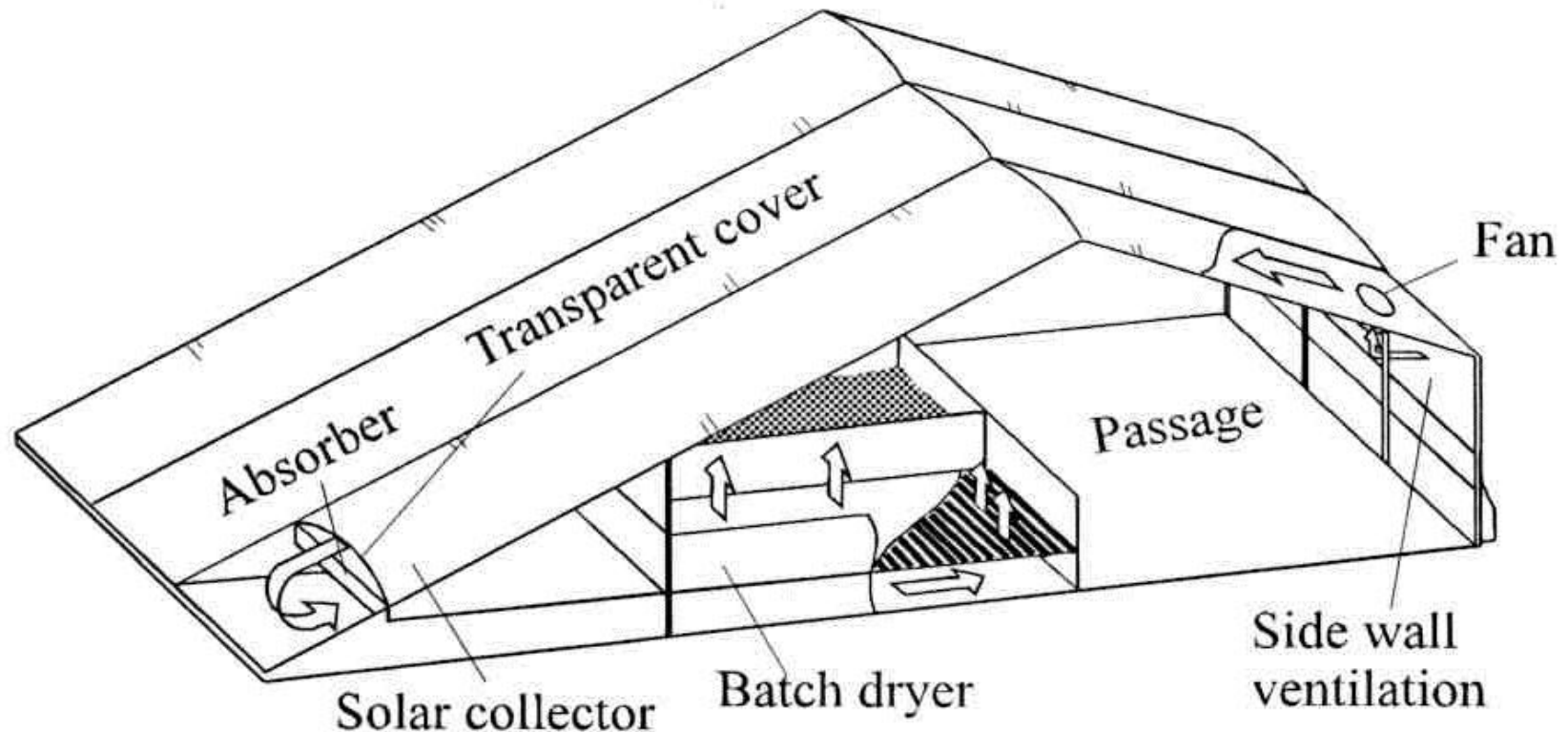
- Drying time, depth of hops in bed and air temperature affect final alpha acid content of dried hops
- Alpha acid content increases during drying, peaks, then declines with drying time, particularly with excessive drying beyond 10%wb.
- Optimal drying conditions for peak final alpha acid seem to suggest drying temperatures of about 48 °C (118 °F) and with shallower bed depths (about 0.2 to 0.4 m or 8 to 16 inches) compared to conventional 1m; and which related to drying times of 8 to 16 hours

General conclusions from prior research –

- Drying at high temperatures and extended drying times can depress the alpha-acid content**
- Drying air temperatures between 100 and 120 F, potentially up to 140 F are considered optimal for hop quality**
- The shallower the hops bed depth, the lower the acceptable air velocity; Air velocities less than 0.3 m/s are recommended for bed depths of 25 cm (10 inches); lower velocity for shallower beds (to prevent bed fluidization and hop damage)**
- Modifying air velocity to lower speeds and cooler temperatures at the end of drying can assist with optimal finished hop quality**
- Final dried hop moisture should be less than 10.5% wet basis to prevent spoilage; and should be greater than 8.5% to prevent cone shatter during handling and storage.**

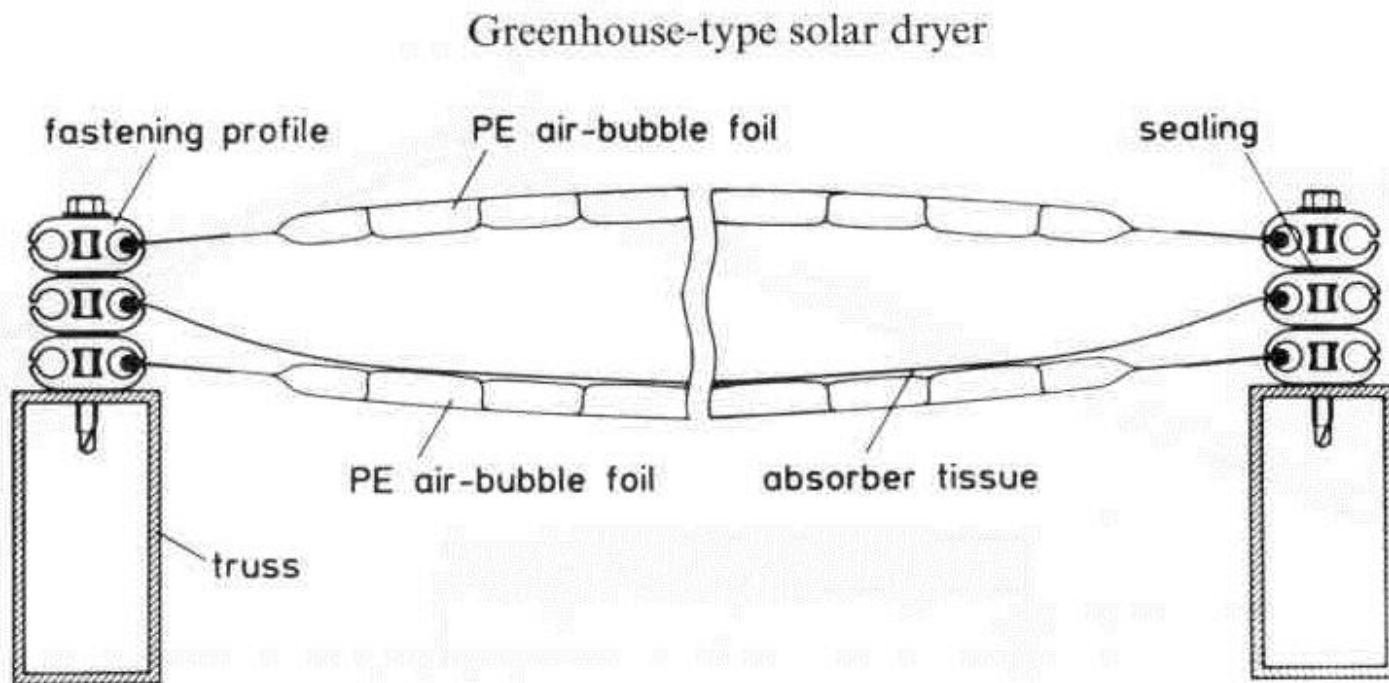
Development of a Greenhouse Type Solar Hop Dryer for Hops and Herbs

Muller et al, 1989, Solar and Wind Tech., 6(5), 523-530.



Muller et al (1988, 1989, 1990, 1992, 1993),
German – Serbian cooperative research solar hop and herb design program.

Cross Section of the greenhouse covering and air plenum for solar heated hot air collection



Ref: Muller et al, 1989 and thru 1993.

Continuation of Muller et al Solar Hop Drying

University of Novi Sad, Yugoslavia (Serbia), Tesic et al (1994)

- continuation of work by Muller et al with same greenhouse solar hot air system
- studied effect of drying time, hop bed depth on hop quality
- found preferred depth to be 55 cm for highest alpha acid
- (used a low alpha variety however; approx. 2% alpha)
- resulted in drying time of approximately approx. **2.8** days for marginal improvement in % alpha; much longer at greater hop depths
- THIS IS CONSIDERED EXCESSIVE DRYING TIME FOR COMMERCIAL OPERATION ; needs to be < 1 day

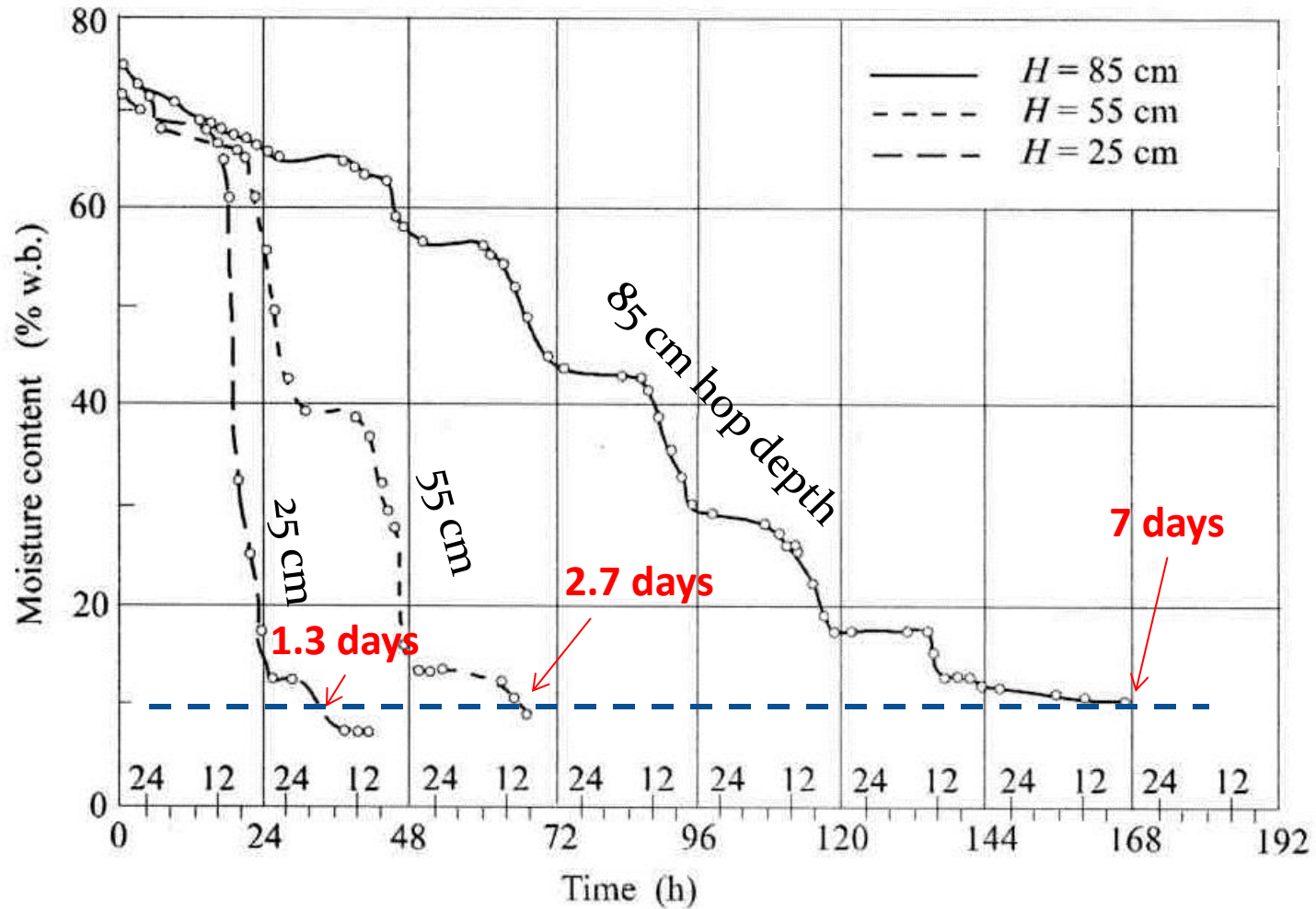


Fig. 3 March of moisture content of different hops layer heights

Illustrates need to use lower bed depth to achieve practical drying times.

Ref: Tesic et al (1994)

Theoretical-Generic Drying Curves for Hops

Hops dry in multiple stages from field moisture _

starting moisture typical 65 to 70+% (wet basis)

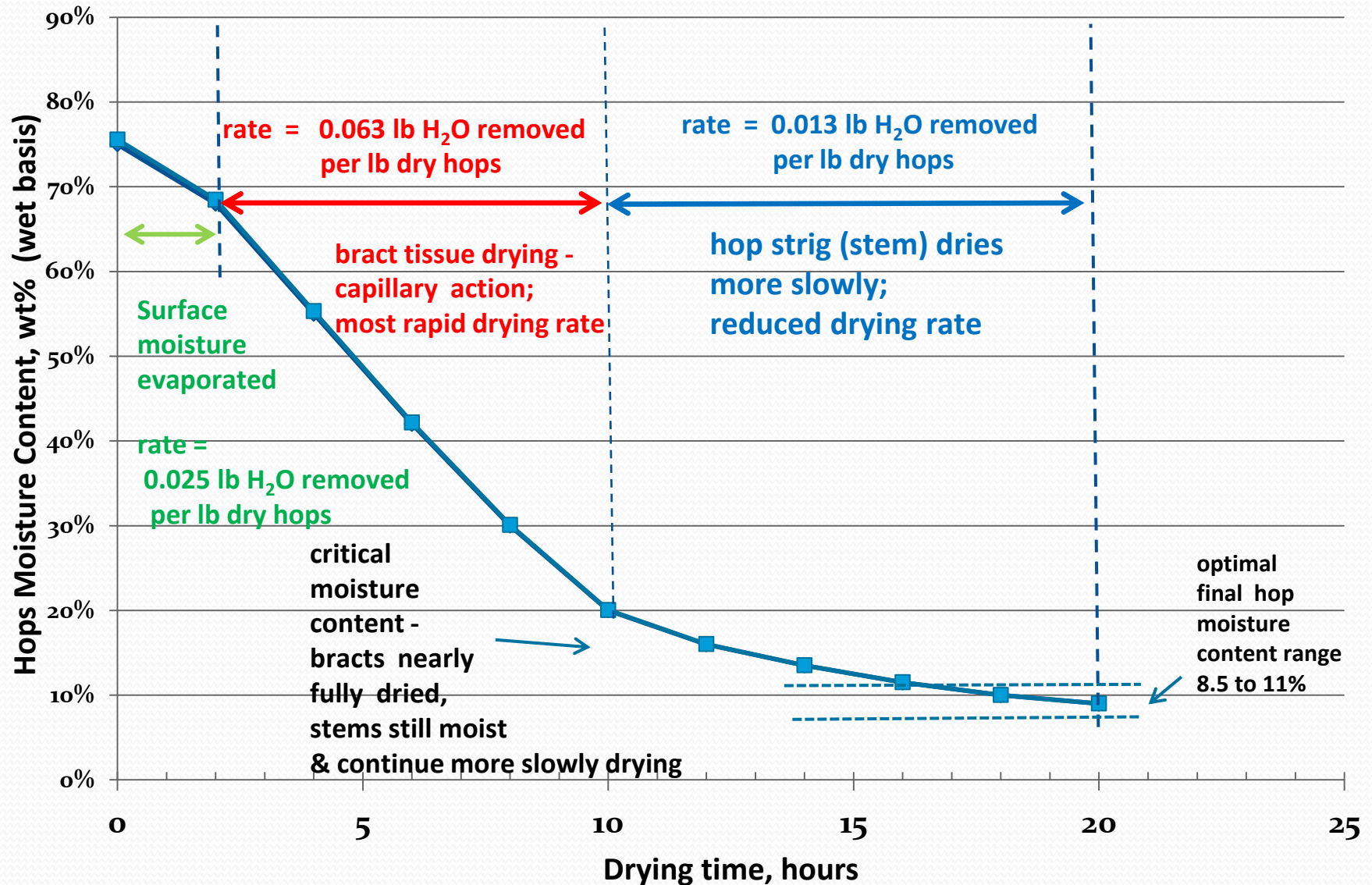
Stage I: surface moisture evaporates from bracteoles

State II: moisture from bracteole internal moisture diffuses out and evaporates

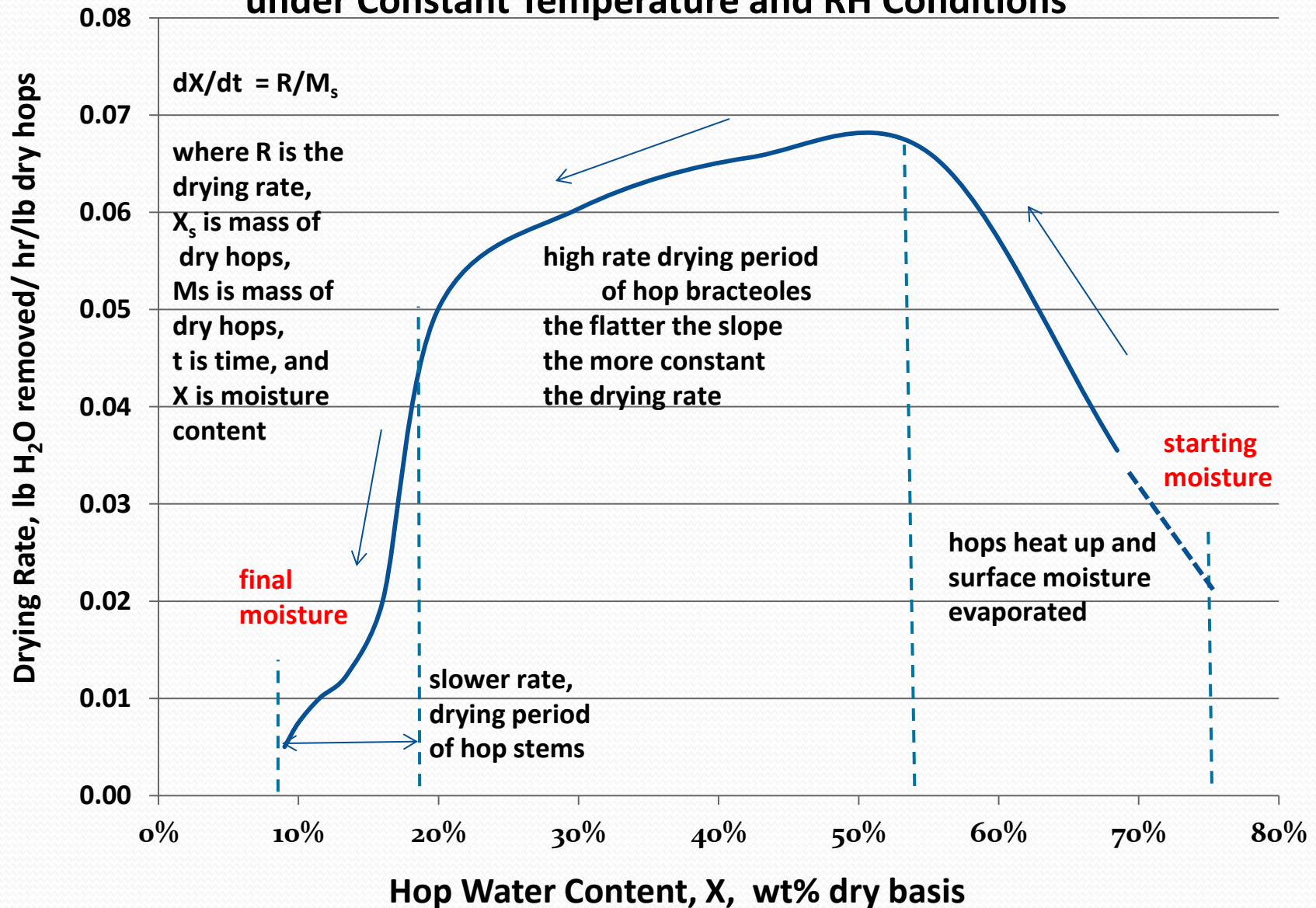
Stage III: strigs (center stem) dries last and more slowly

Generic drying curve and drying rate curves are illustrated on following two graphs. Rate curve is dX/dt and progresses from right to Left, where X is the dry basis moisture of hop and t is time.

Generic Hops Drying Curve



Generic Hops Drying Rate Curve under Constant Temperature and RH Conditions



Drying Duration and Rate Relationships –

Henderson (1958)

$$\ln [(M_t - M_e)/(M_0 - M_e)] = -k p_s V^n t$$

Where M are moisture values at time t, time 0, or at equilibrium e and V_n is velocity, p_s is saturation water vapor pressure, and t is the drying time

For temp range 110 to 150 F (43 to 66 C); V of 30 to 50 cfm (0.11-0.19 m/s)

Bailey (1958)

$$t = [1/(P-p)] \times [(24.7/0.95 V) + (20260/0.39 V)]/60 = \text{minutes}$$

Where V is air speed (m/s), P is total pressure, p is partial water vapor pressure at temperature T

Considered valid for V range of 0.17 to 0.2 m/s, T range of 58 to 66C

Drying Duration and Rate Relationships (cont'd) –

Zeisig (1970) –

$$t = 24.8 / (1.885 (P - p) + 0.1 V [(15 L / V) + 910 / V^2])$$

Where t is drying time (minutes),

P is total pressure (mm Hg)

p is water vapor partial pressure at temp T (in mm Hg),

V is air velocity (m/s), and

L is quantity of water dried from hops (kg/m²)

Range of conditions:

0.55 to 1.17 m/s air velocity

75 to 100 C (167 to 212 F)

Some fossil fuel fired hop dryers -



**Mac Hops Ltd.
Moteuka, New
Zealand**

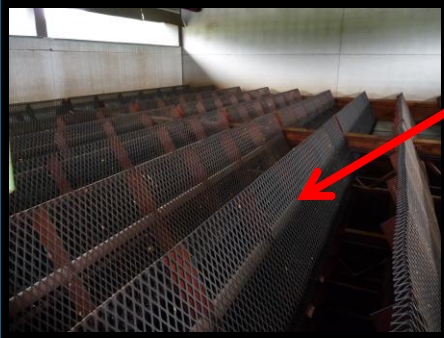
**Conventional kiln;
Coal fired boiler,
indirect heated hot
water –hot air heat
exchanger; dry at
140 to 150 F, 1 to
1.1 m deep; 8 hour
drying time**

Multi-decked louvered floor counter-current flow hop dryer

New Hoplands, Tapawera, New Zealand



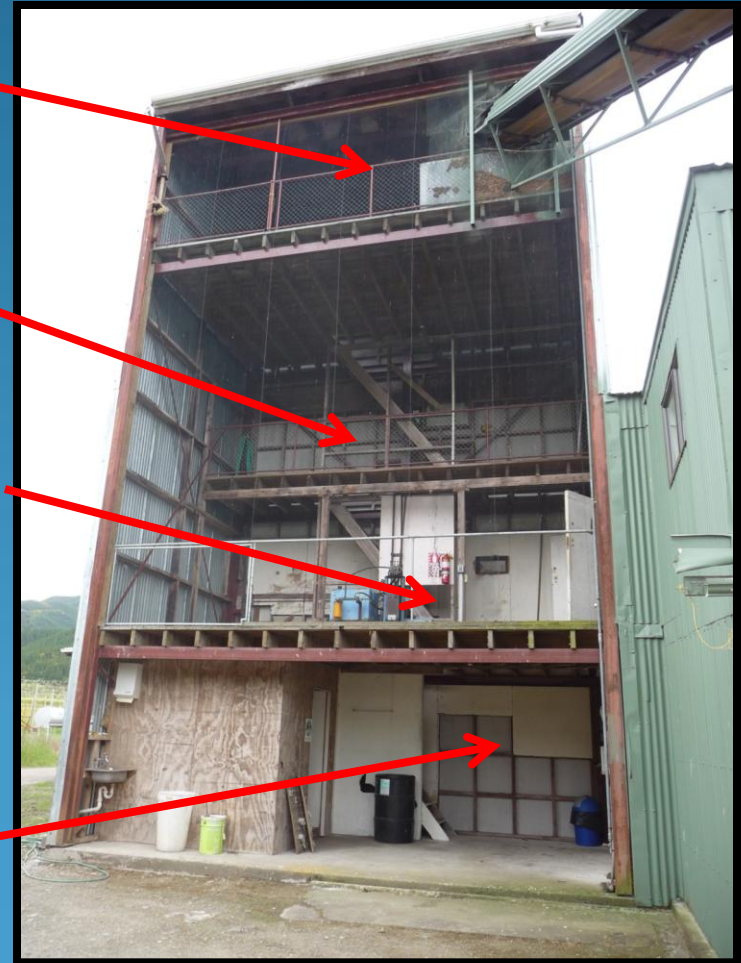
Hops bed distributor on top deck



Middle two decks, louvered floor, open position



Bottom deck, with humidity controller, hop removal by moving fabric floor



Coal fired boiler, heat exchanger, updraft hot air distributor

Original Style Oast House Hop Drying Kilns

Bushy Park Estates, near Hobart, Tasmania (Australia)

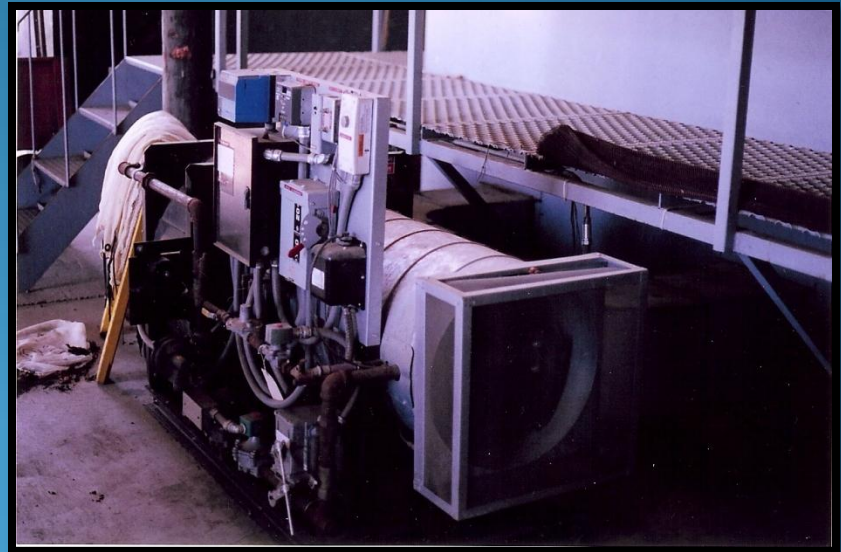


Small scale natural gas fired hop dryer

USDA/ARS Hops Research Station, Corvallis, Oregon



5'x5'x'3 drying bed



**Natural gas burner ; temperature
and fan controls**

Solar Hop Dryer CSU - GREG

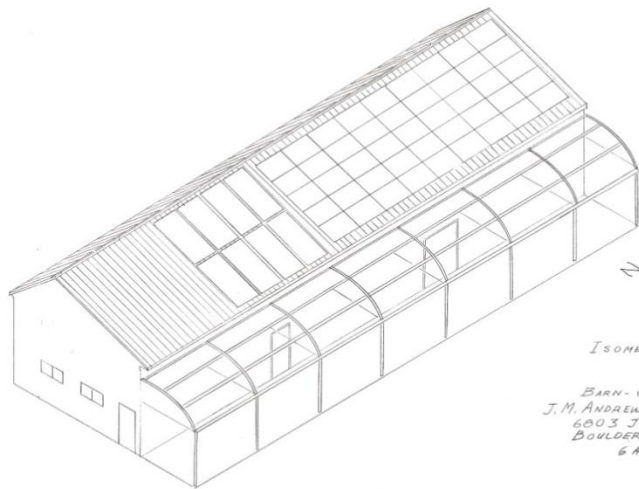
Research Results 2010 - 2012

- **2010** Limited ambient air drying tests; system construction
- **2011** 7 solar drying tests with ambient air,
Low level greenhouse air, greenhouse hot air
roof plenum collection system
- 2012** 14 solar drying tests with hot air greenhouse
2012 plenum system under various hop bed depths,
2013 and air velocities

Solar Hop Drying Research & Development Needs :

- Need to keep drying times short, preferably < 0.5 to 1 day
- Need to develop good sensor and control systems to monitor hop drying progress
- Need simple and effective method to determine completion of drying (when 10% moisture achieved)
- Need to keep capital & labor costs as low as possible
- Keep parasitic energy costs as low as possible
- Automate system as much as possible to reduce manpower requirements
- Need to achieve optimum hop quality & storability
- Need to define best operating parameters (temp, humidity, air velocity, bed depths, etc.)

Illustration of Solar Greenhouse (under construction 2010)



ISOMETRIC
BARN - G
J. M. ANDREWS
6003 J
BOULDER
6 AM

**Isometric rendering
of attached greenhouse
on south side of barn
84 ft by 10 ft;
photovoltaic collectors
on barn roof**



Andrews Family Hops and Herb Dryer (2010 configuration)



Above:
Dryer tray (one of six; 42" x 42" x 10")
1/2" mesh bottom overlaid with plastic
screen)

Below: Overall view of hops dryer in
first test year 2010; using ambient air
and greenhouse fan only



2010 Hops Ambient Air Dryer Performance

- Used 6 inch depth of hops in trays, stacked three high for total hops depth of 18 inches per stack; 84 total sqft bed area
- Each tray held approximately 10 pounds fresh weight hops
- Typical ambient air temp during drying was 69 to 73 F;
- Relative humidity less than 25%
- Total drying time for approx. 8to 10% final moisture was 14 to 15 hours
- Air velocity not measured in these early incomplete tests
- Interpretations and Conclusions:
 - Using only ambient air to dry, the required drying area is approximately 0.26 to 0.29 sqft of tray area per pound of dry hops
 - For an estimated yield of 1200 dry pounds per acre would require a total drying area of 312 to 348 sq ft of bed area, or 1/10 of that assuming a picking/processing rate of 0.1 acre picked per day

Solar Hop Drying Tests - 2011

- 3 bays of greenhouse completed and hot air hop dryer collection system constructed
- data logging system installed with temperature and humidity sensors
- seven solar drying tests run with various ambient weather conditions; some hot dry, others rainy cloudy
- 3 different solar hot air collection systems tested
- 4 solar drying tests run with greenhouse roof hot air plenum solar collection system

Solar Hop Drying Tests - 2012

- 3 bays of greenhouse completed and hot air hop dryer collection system constructed
- enhanced data logging system installed (more temp and RH loggers with digital displays)
- 14 solar drying tests run with various ambient weather conditions; most hot dry, minor rainy cloudy events
- modifications of blower and motor drive system
- multiple air velocity combination tests (0.025 to 0.23 m/s)
- more multi bed tests
- various starting times: morning, afternoon, evening
- variations in hop depths in trays (2.5 to 5.25 “)

Solar Dryer – Greenhouse Hot Air Plenum Intake



Collector plenum on inside of greenhouse roof
216 ft² (19.4 m²),
12 ft wide x 18 ft long (3.6 x 5.4 m); external polycarbonate twin wall greenhouse glazing; 5 inch (12.7 cm) deep air gap between arch trusses; woven black shade cloth layer and black polyethylene plastic film on bottom of plenum



Solar hot air plenum ducting collection system (plenum on upper right; 10" dia. galv. Ducting, upper center to lower center; insulated flexible ducting into dryer inside barn at lower left)



Hot air collection ducting
connecting to squirrel cage
blower into air distribution
channel of dryer



Blower with multi-sheave driver and driven belt pulleys for variable speed operation; wire leading away is thermocouple at dryer inlet



**Overall view of
dryer-**
six dryer trays in
two stacks;
hot air upflows
from distributors
below; system
constructed using
pallet rack frame



Hop drying trays -
½" galv. wire mesh
bottom covered with
plastic screening;
14 ft² (1.3 m²) per tray;
12 in deep (30.5 cm)

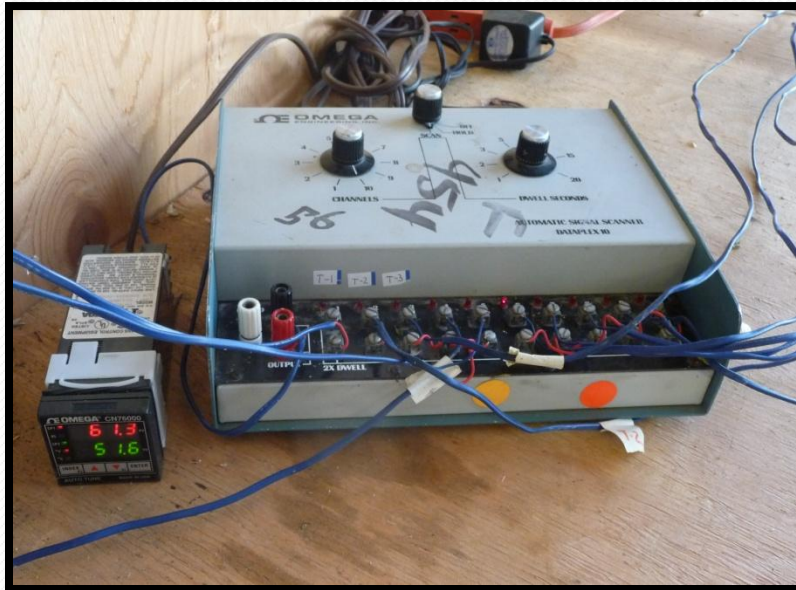


Hop drying trays –
Filled with dried hops
ready for bagging and
weighing; bagged dry
hops in background





Instrumentation & sensors –
top left – digital temp and RH data logger (Extech; Lascar Electronics);
 9 in system; btm left - type T thermocouple readout and Omega 10 channel dataplex signal scanner;
btm right – hot wire anemometer (air velocity meter) and sensor tip





Hop Moisture analysis –

top left - analytical balance (0.01 g) for hops moisture analysis;



btm left - lab oven and other balances for moisture analysis

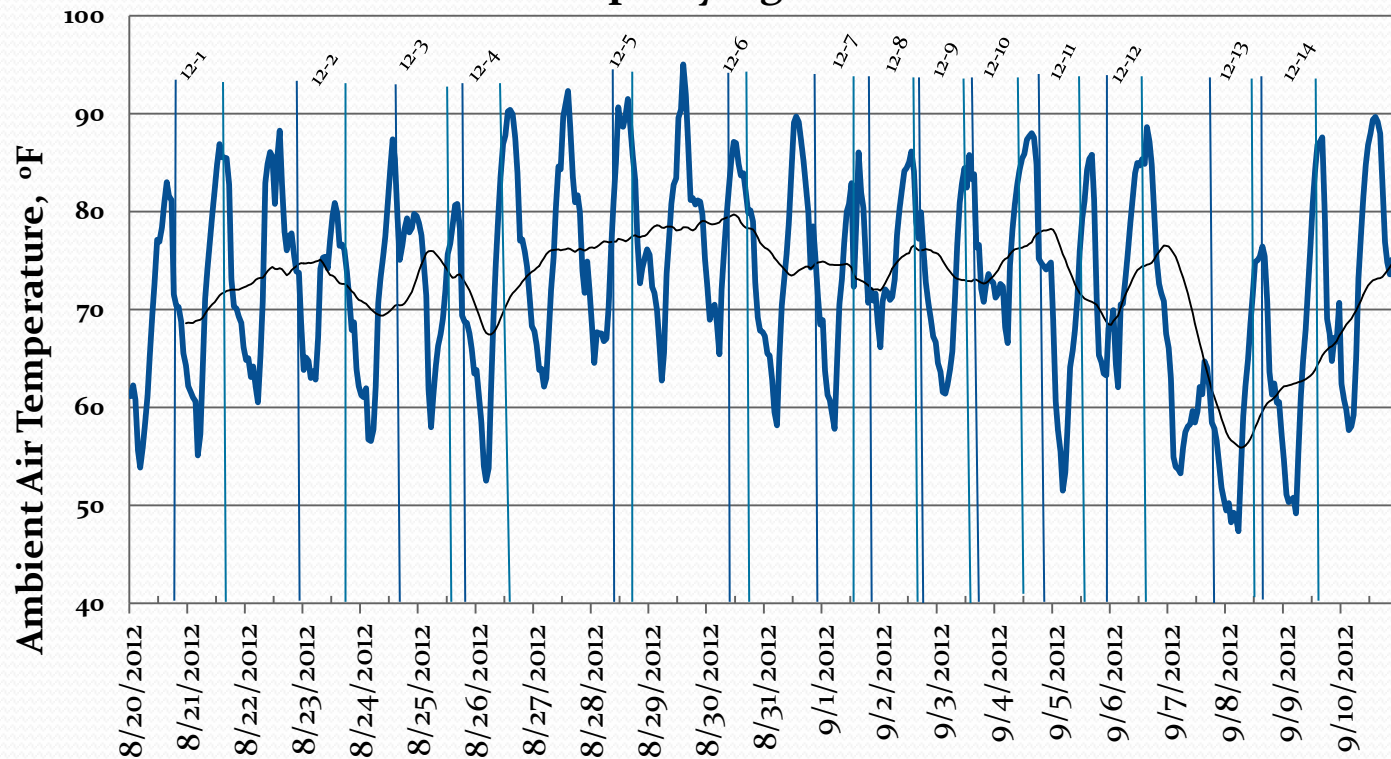
Meteorological Data -

- Site ambient meteorological data was collected from data loggers
 - Temperature
 - Relative humidity
 - Instantaneous watt output from inverter panel of solar PV on barn roof .
- Local complete weather station data downloaded from Northern Colorado Water Conservancy District weather station, NW Boulder Station # 633
 - Solar radiation, and clear sky radiation, cal/m²
 - Hourly average temperature, dew point, relative humidity, rainfall

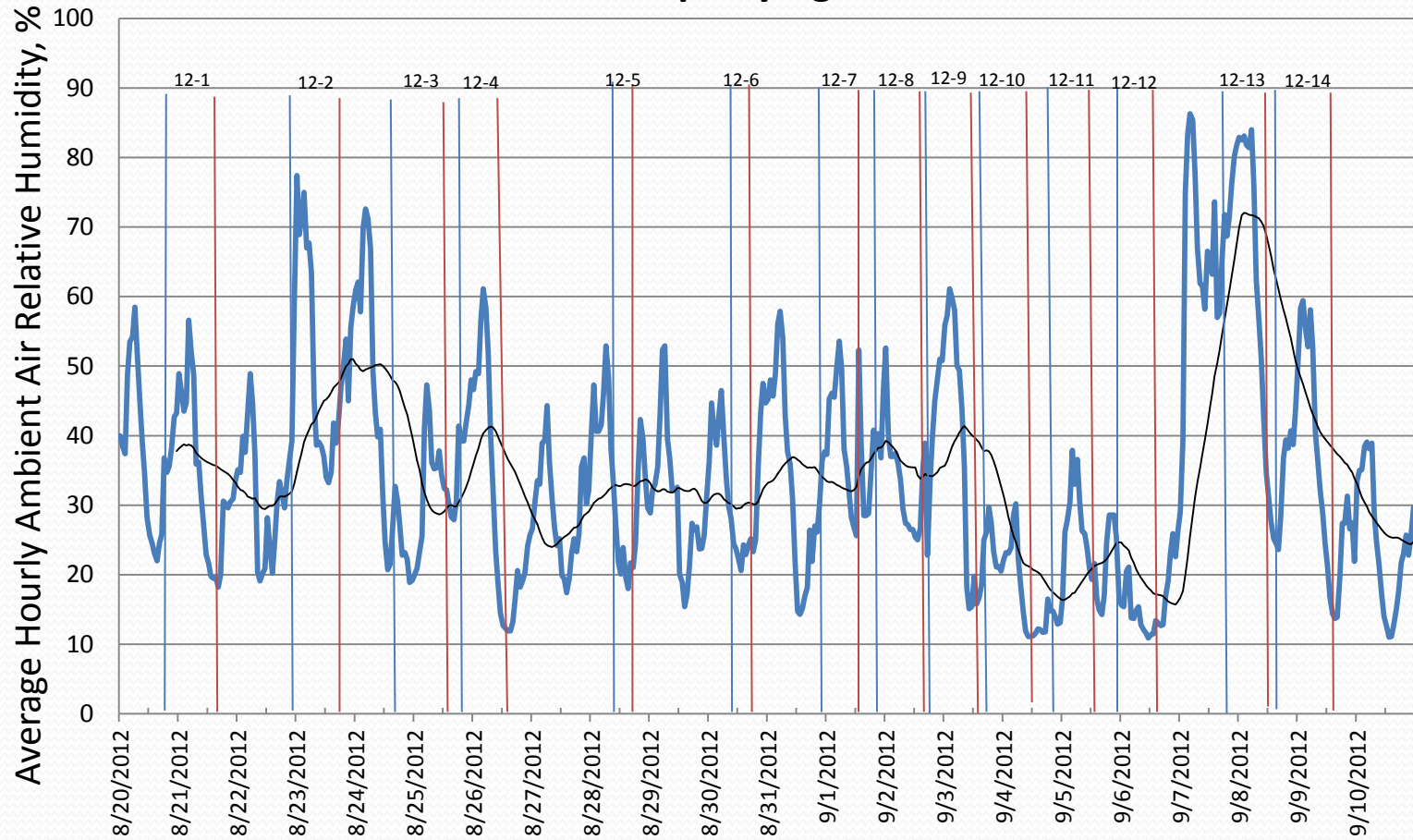
Examples of Meteorological Data

2012 Hop Harvest Period

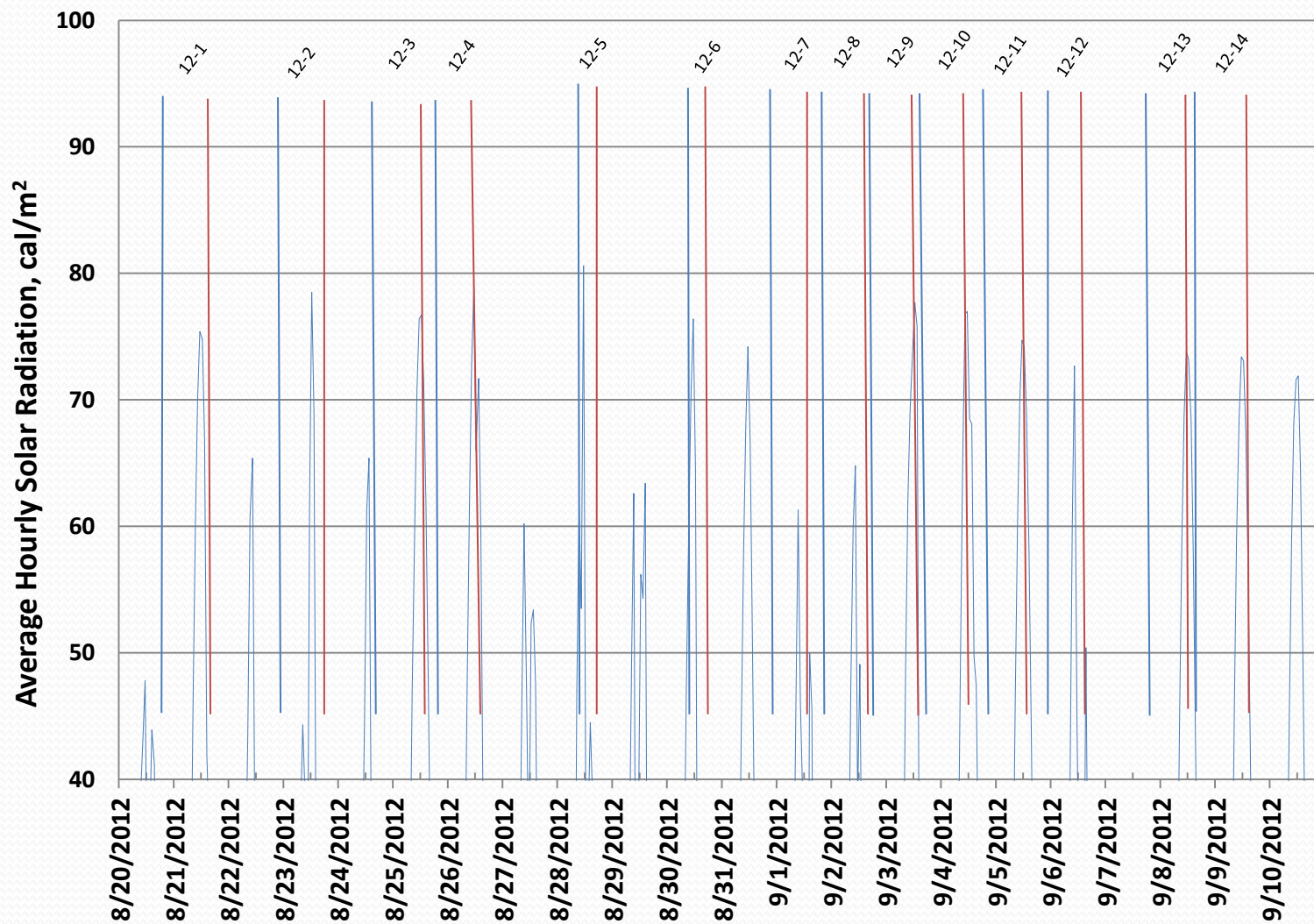
Average Hourly Ambient Air Temperature (°F)
Full 2012 Hop Drying Test Period



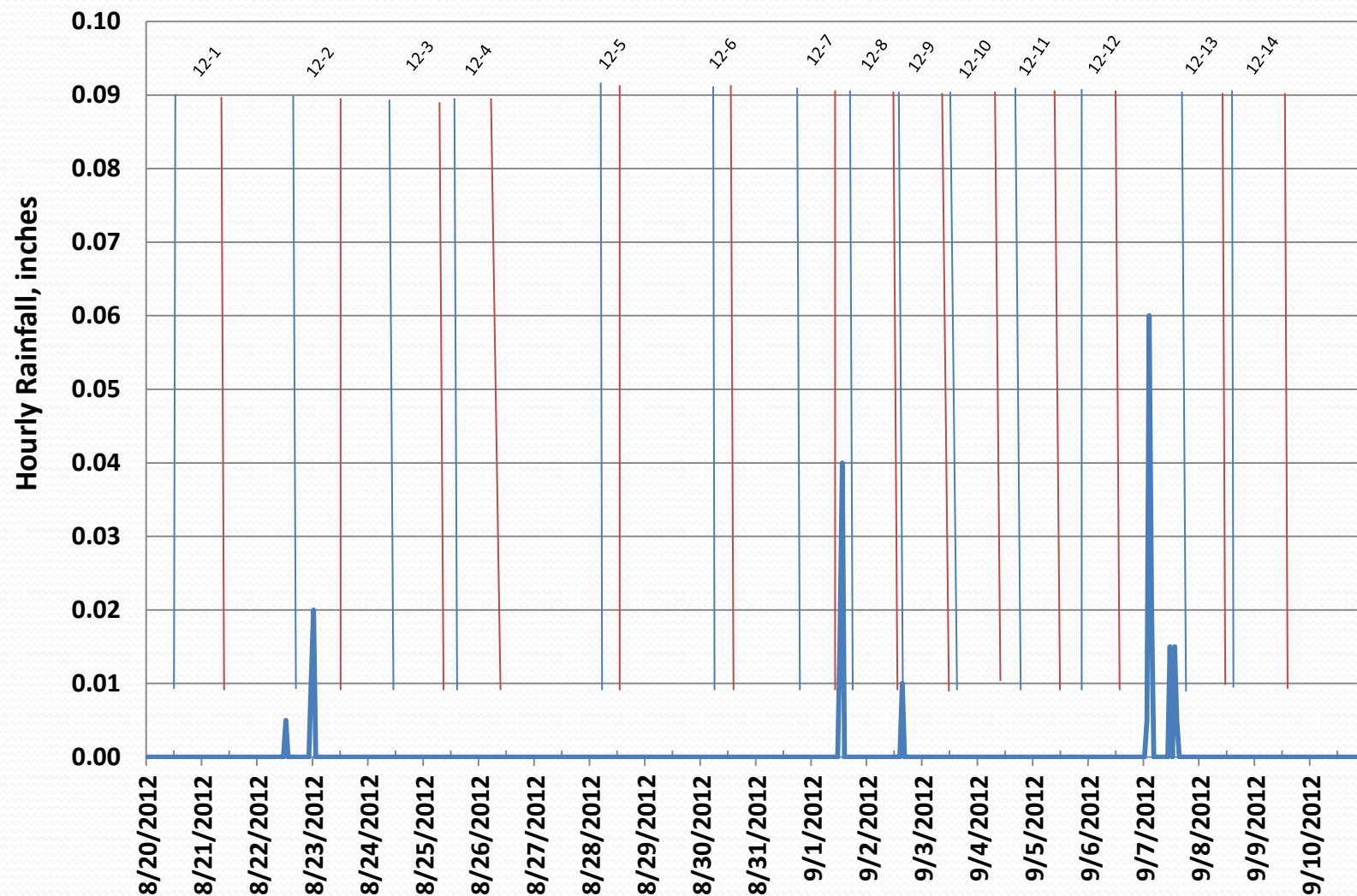
Average Hourly Ambient Air Relative Humidity % 2012 Full Hop Drying Test Period



Average Hourly Solar Radiation, cal/m²
2012 Full Hop Drying Period



Hourly Rainfall, in 2012 Full Hop Drying Period



Solar Hop Drying Test Data – Test # 12-14 Sept 8-9, 2012

Test conditions summary:

three drying trays; two in left stack; one in right stack

2.5 to 5.5 inch (6.4 to 14 cm) deep hops in trays

dryer inlet temp range: 52 to 135 °F (11 to 57 C)

air velocity thru bed: 0.11 to 0.14 m/sec (0.36 to 0.46 ft/sec)

drying overnight with fan on continuously

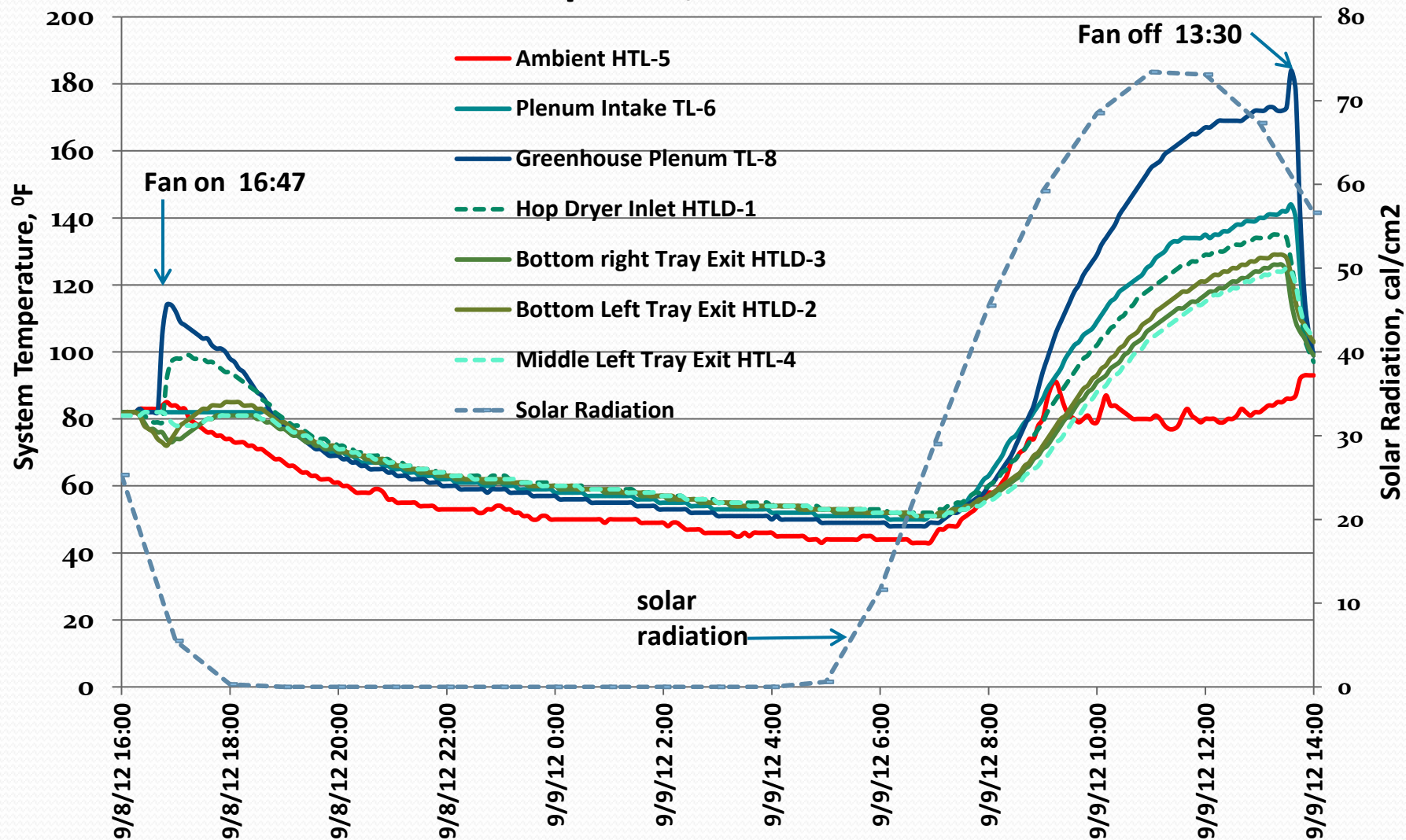
start drying at 16:47 hours; stop drying at 13:30 hours

total drying time: 18 hours to reach 10% moisture

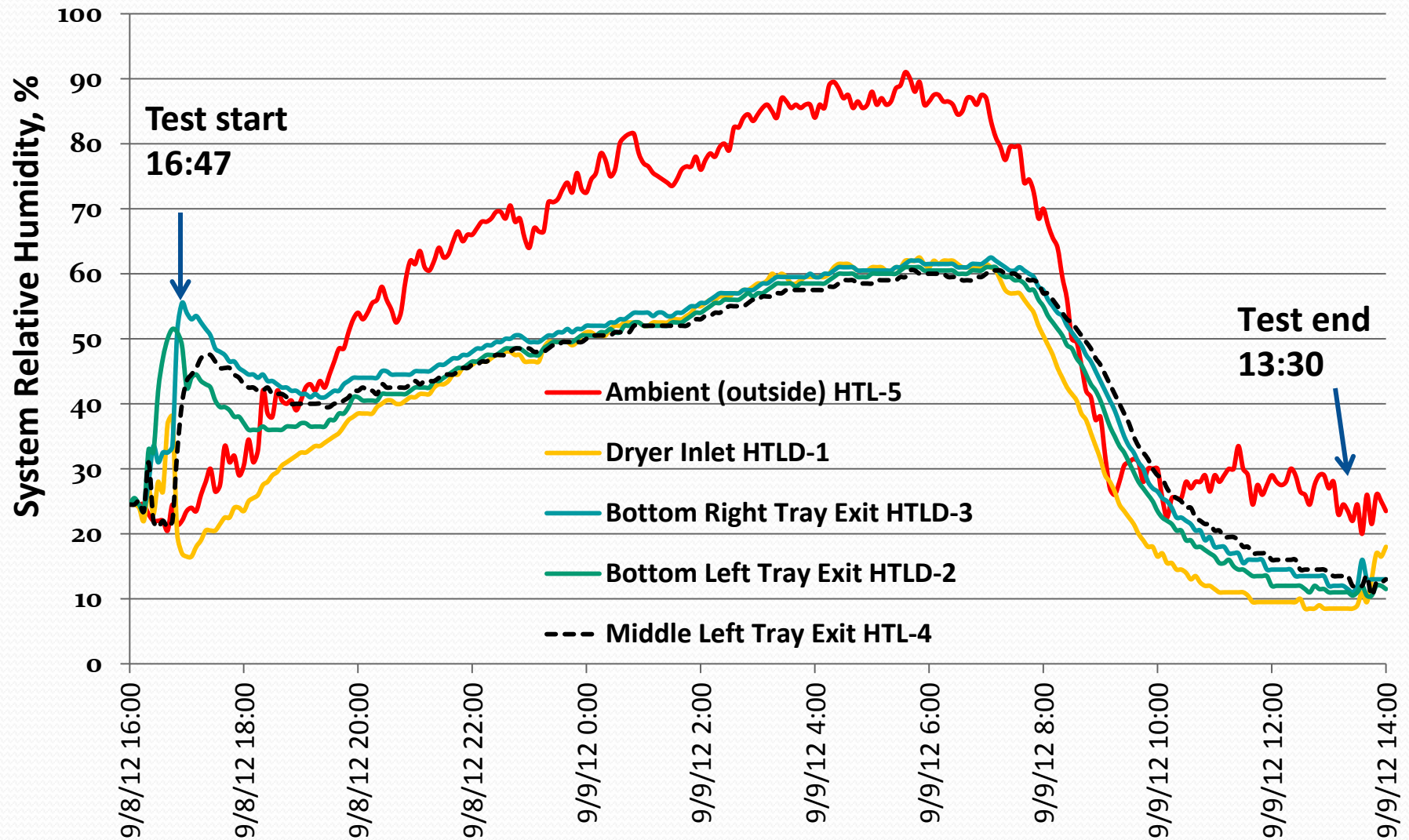
weather, partly cloudy and cooler

Solar Dryer System Temperatures, Test 12-14

Sept 8-9, 2012

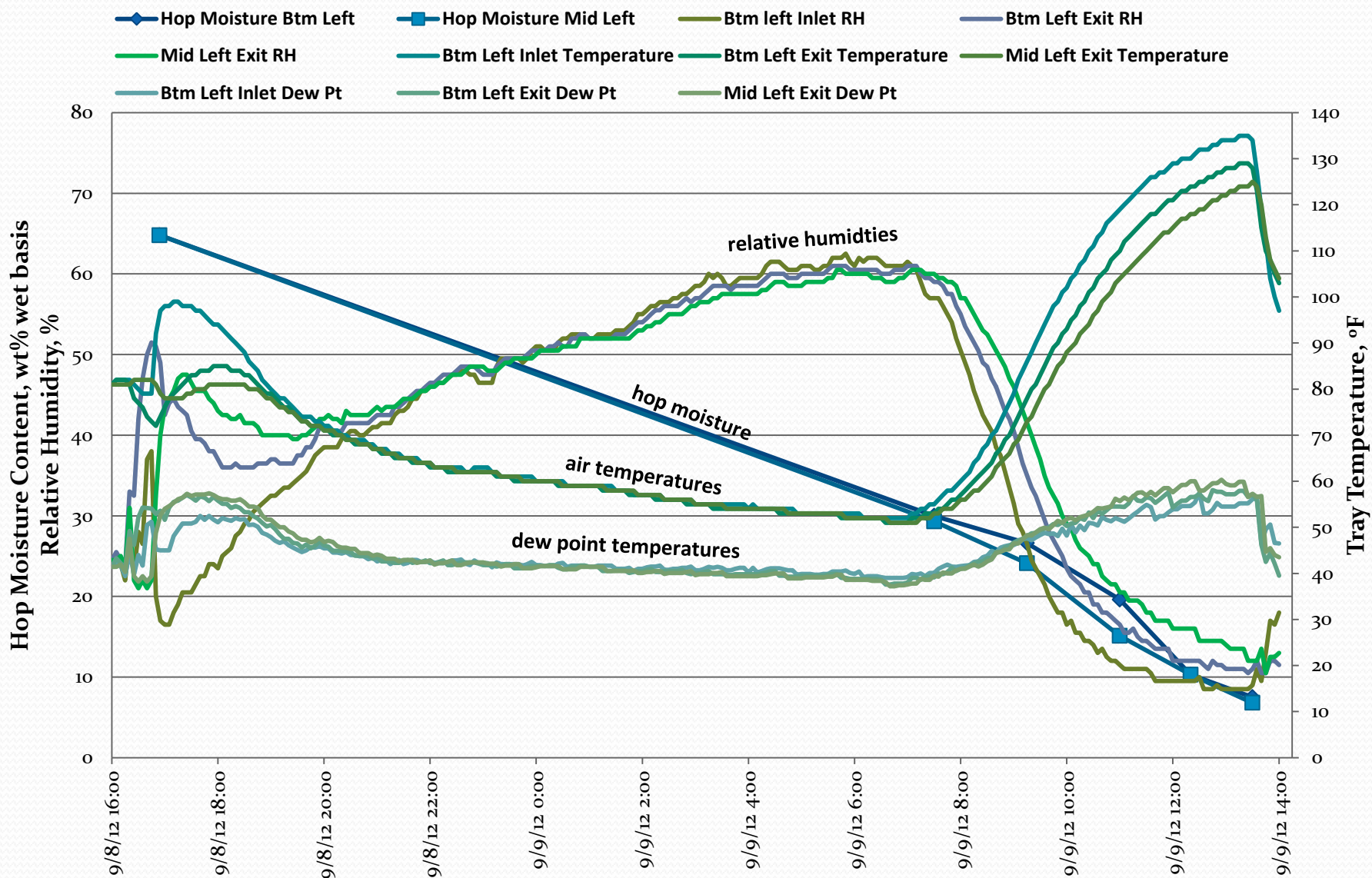


Solar Dryer System Relative Humidities Test 12-14, Sept 8-9, 2012

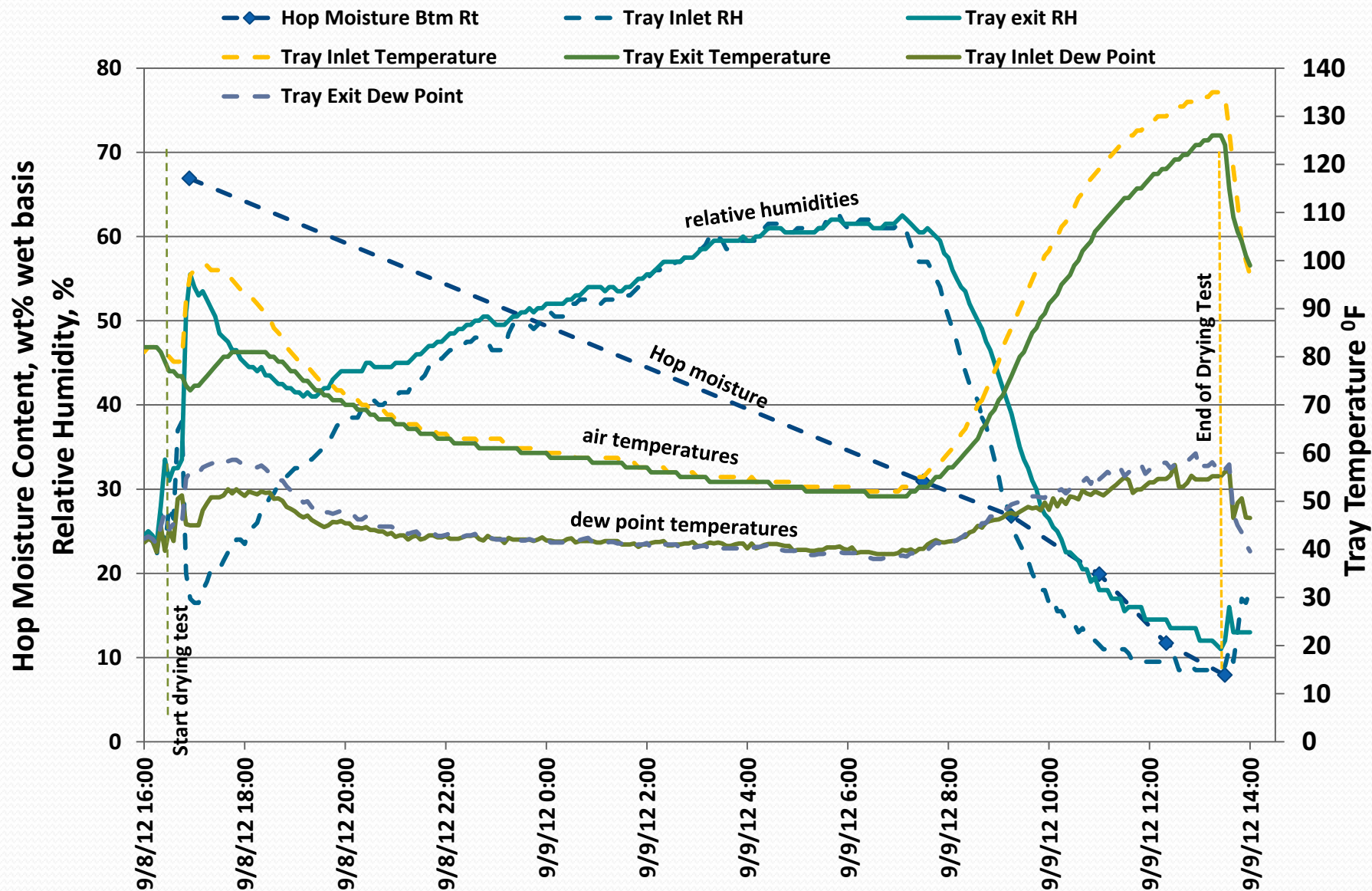


Bottom & Middle Left Tray Drying Conditions Solar Hop Drying

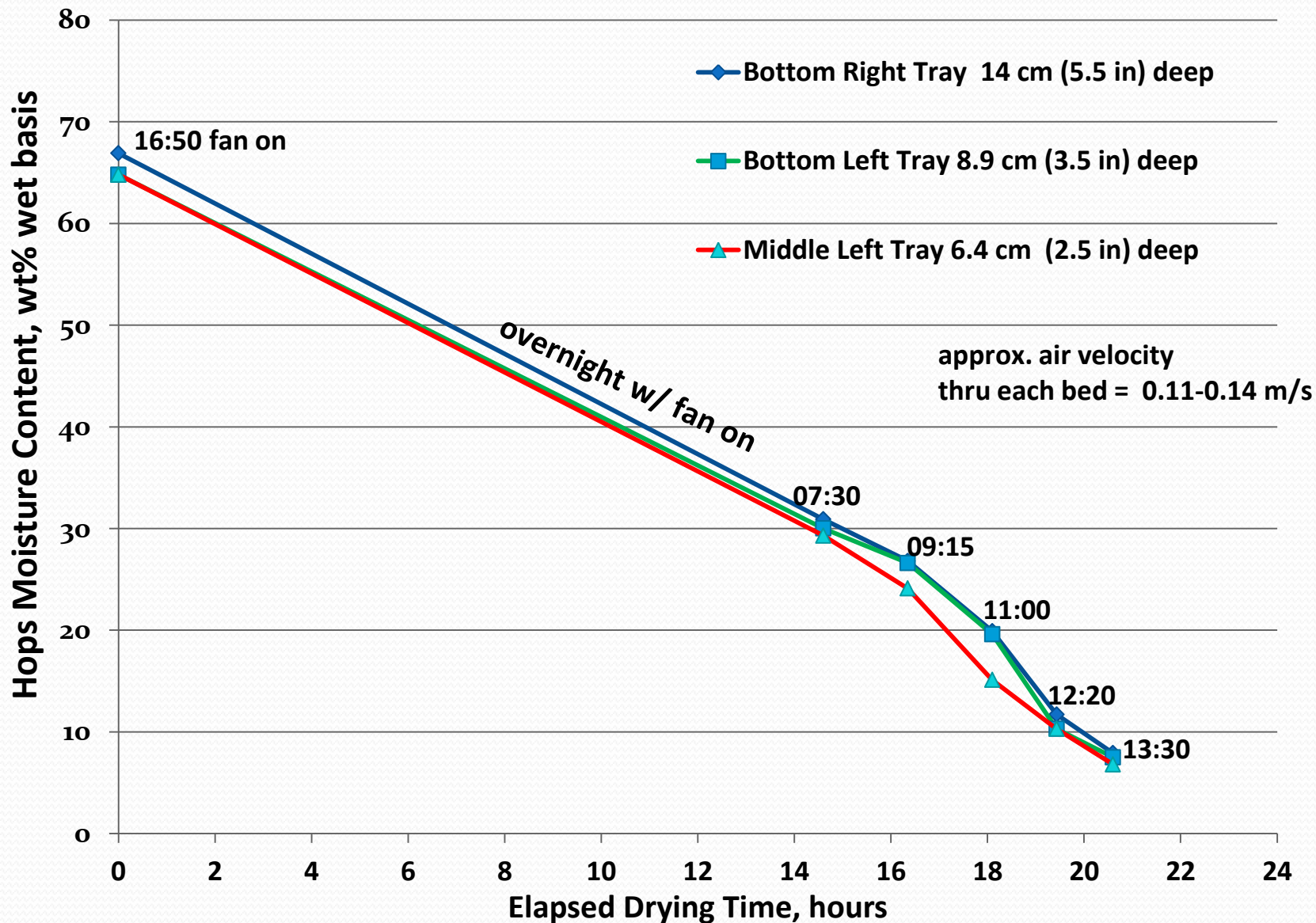
Test 12-14, Sept 8-9, 2012



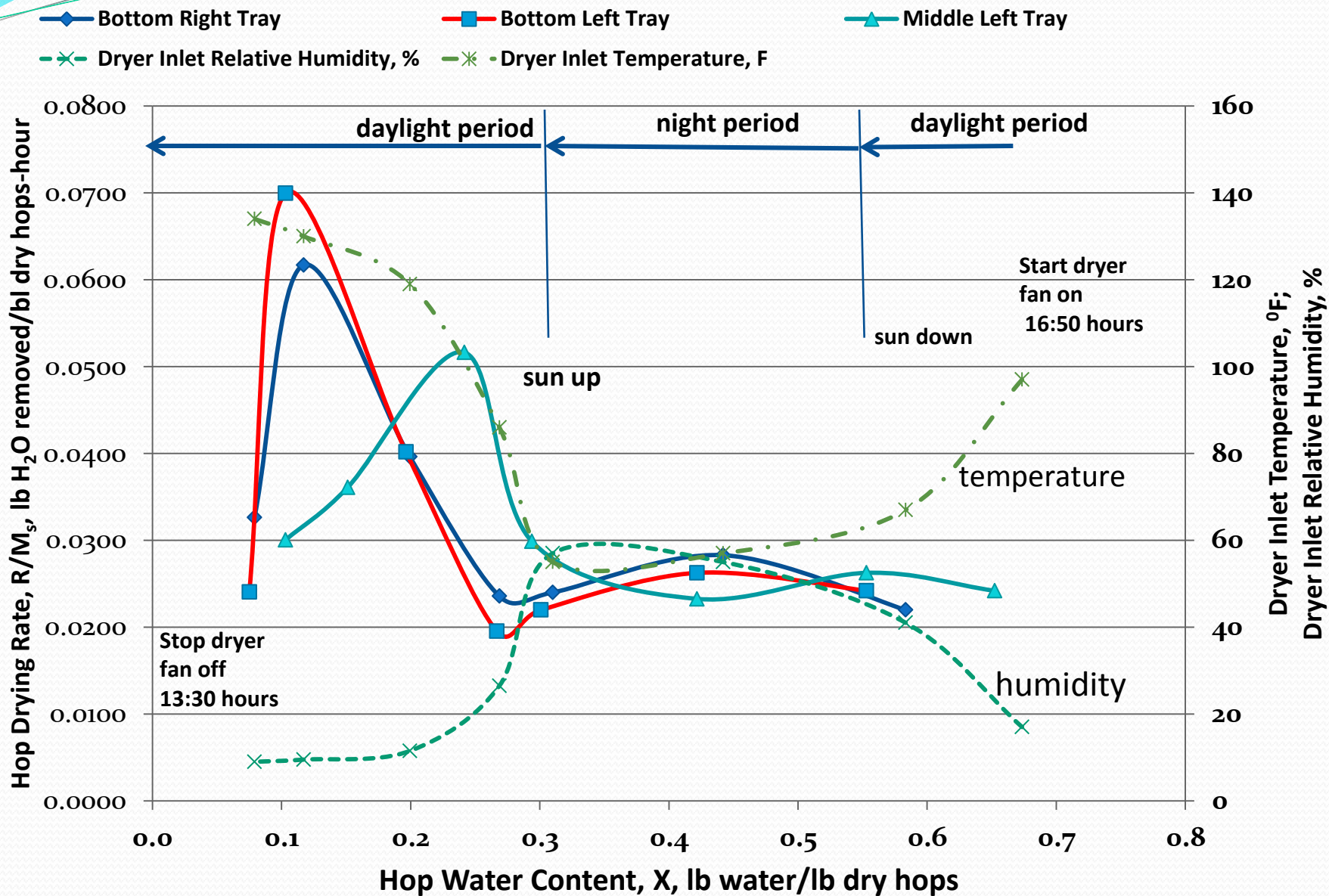
Bottom Right Tray Drying Conditions Solar Hop Drying Test 12-14, Sept 8-9, 2012



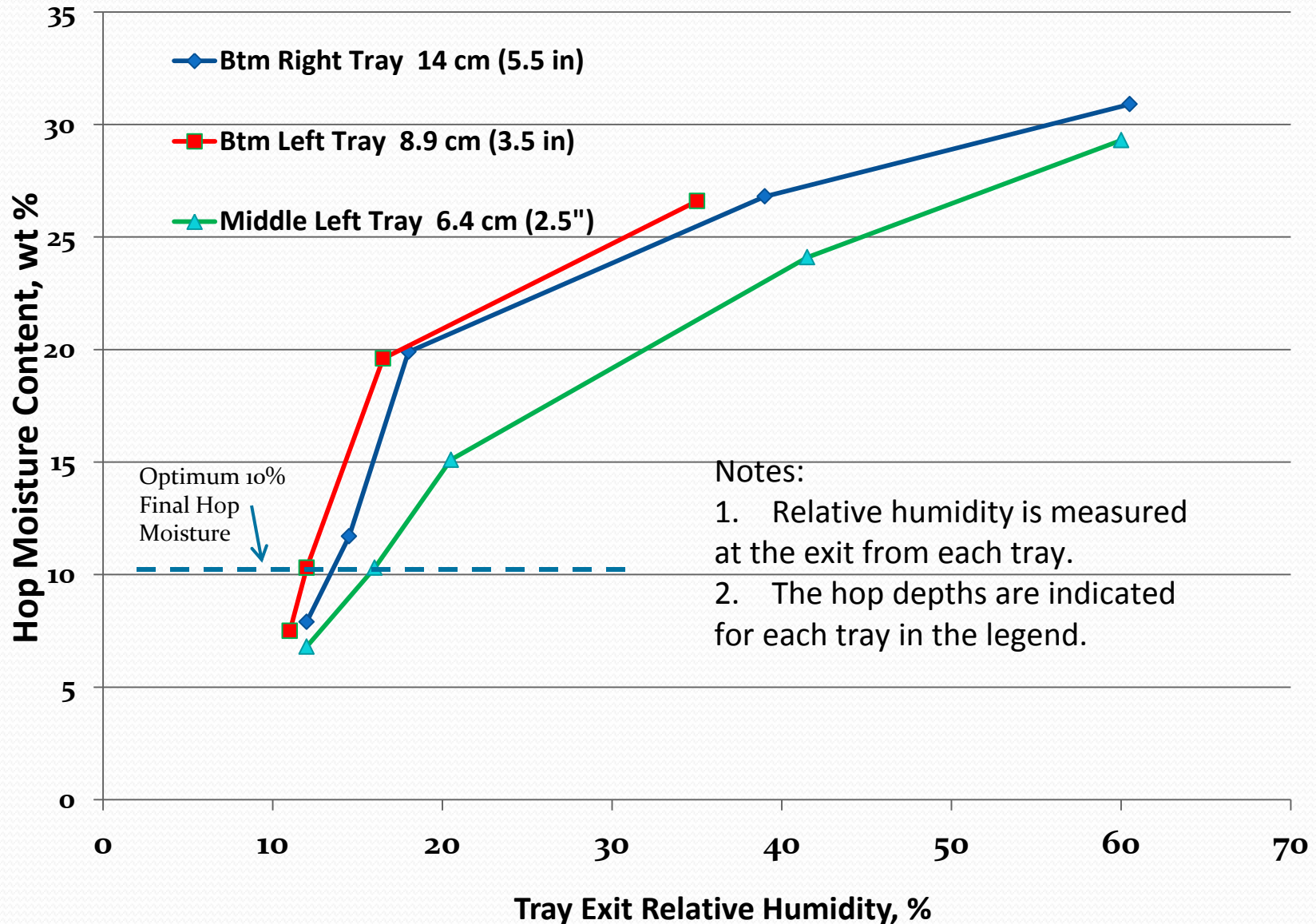
Hops Drying Curve, Test 12-14, Sept 8-9, 2012



Hops Drying Rate Curve (dry basis) Test 12-14, Sept 8-9, 2012

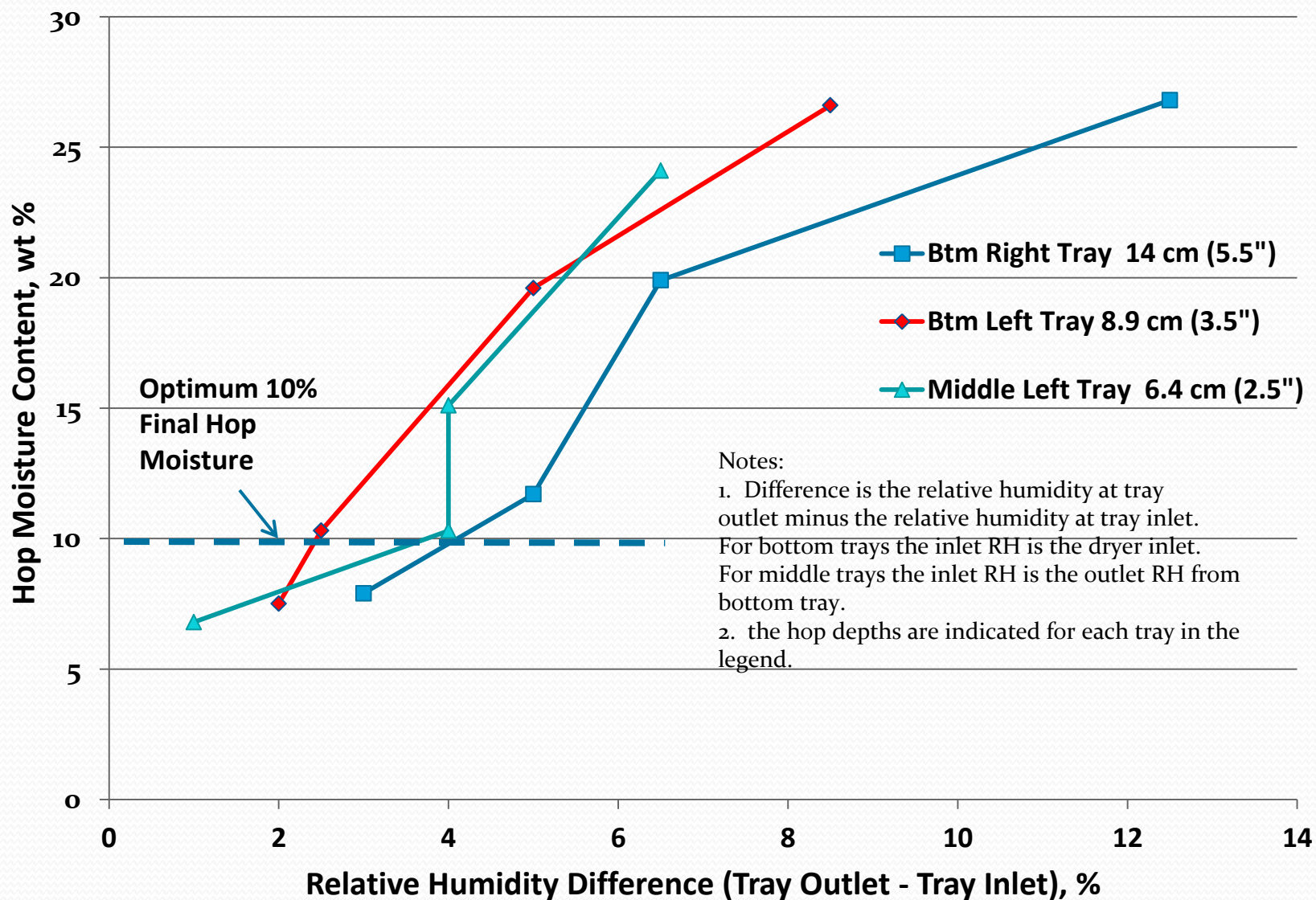


Tray Exit Relative Humidity vs. Hop Moisture % Solar Hop Drying Test 12-14, Sept 8-9, 2012



Relative Humidity Difference vs. Hop Moisture

Solar Hop Drying Test 12-14, Sept 8-9, 2012



Solar Drying in New England vs. Colorado

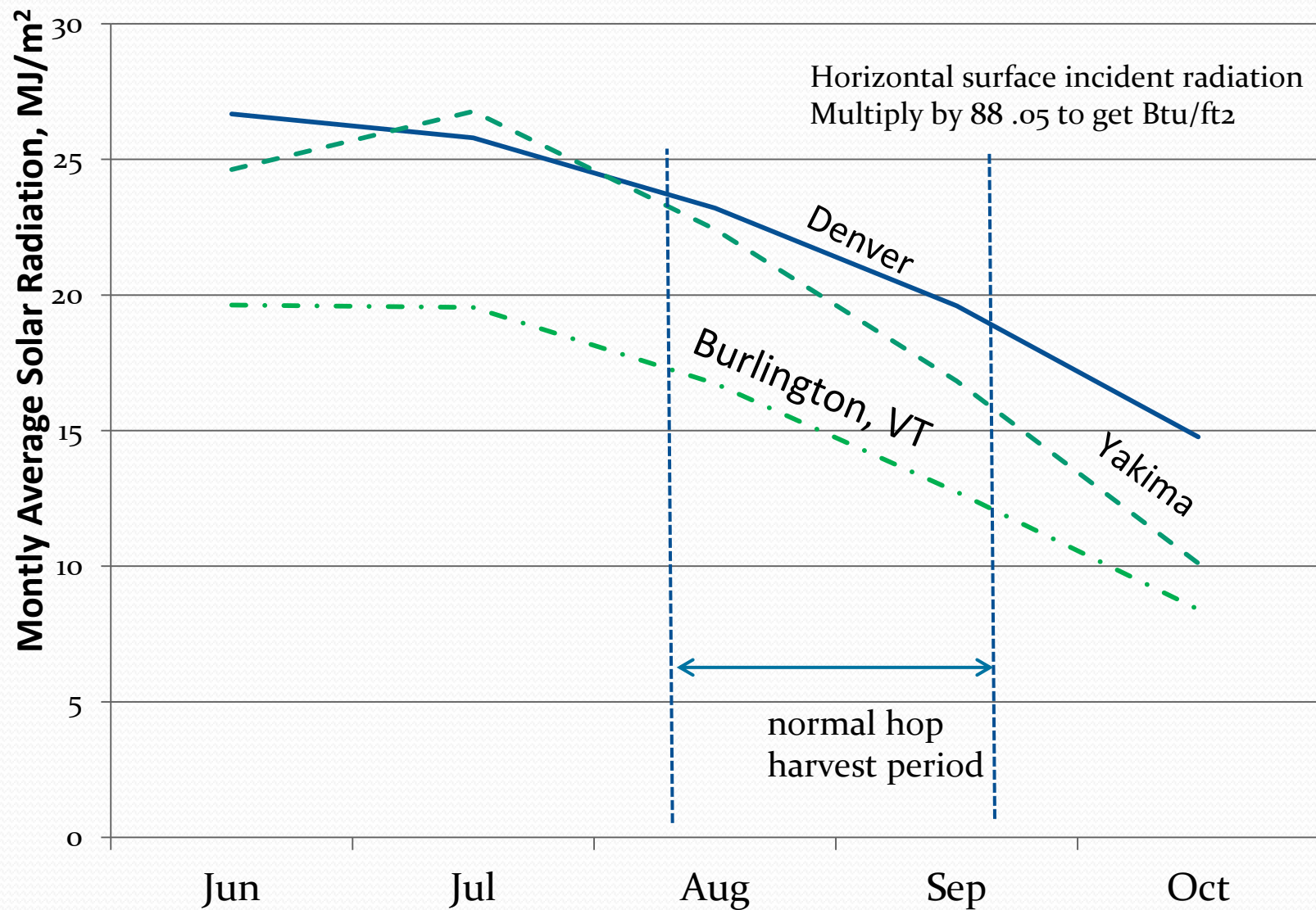
Site conditions differ between Denver, CO and Burlington, VT

- latitudes differ by about 5 degrees
(Denver 40 N, Burlington 44.5 N)
- moderately longer day length during hop harvest season

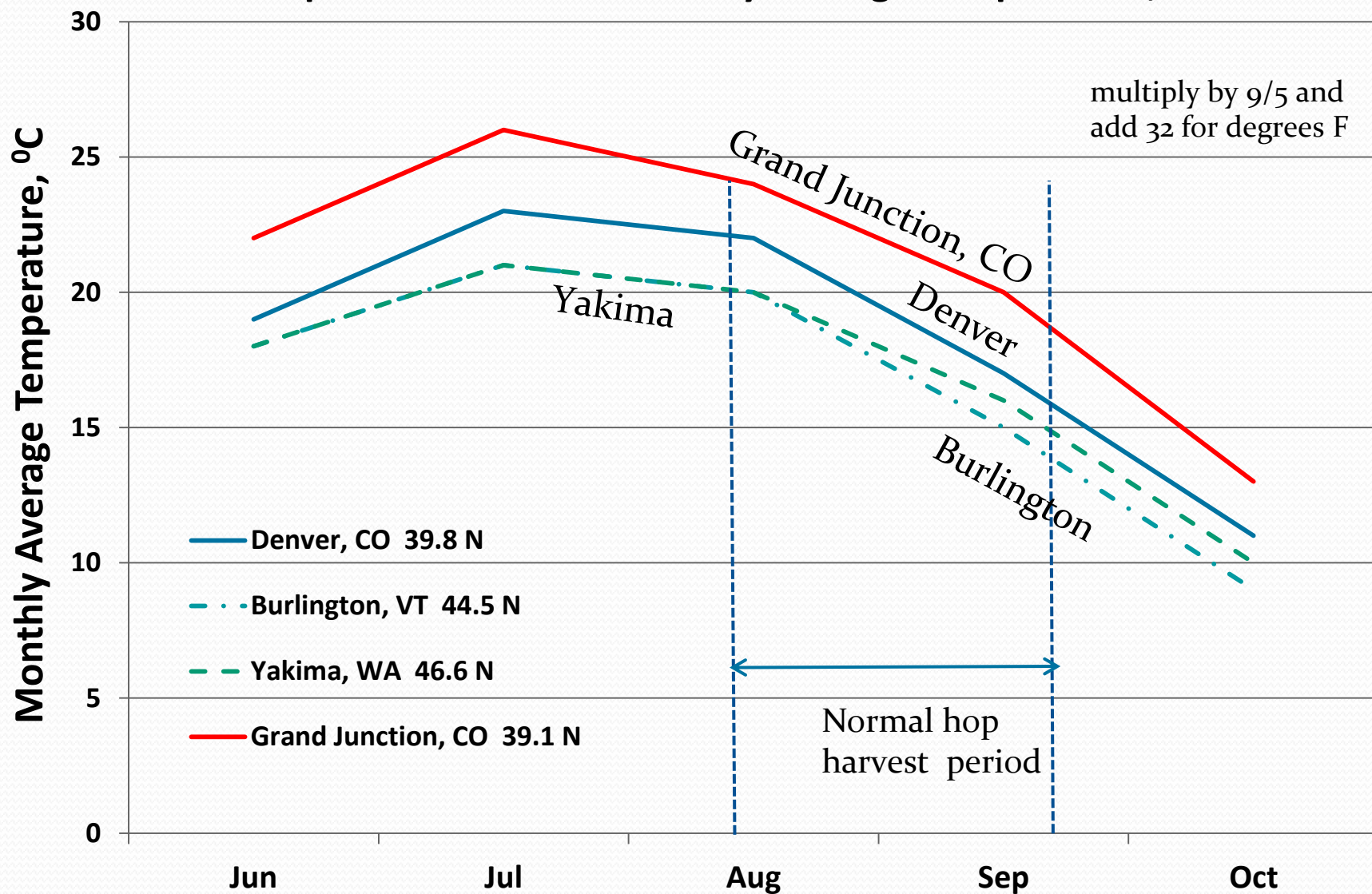
Weather conditions during August – September differ

- Burlington, VT approx. 5 MJ/m² less monthly solar radiation ,
mostly due to cloudier conditions than Denver, CO
- Burlington, VT generally 3 °C cooler and more humid than
Denver during hop harvest season

Comparative Monthly Average Solar Radiation, MJ/m²



Comparative 24 Hour Monthly Average Temperature, °C



Comments on solar drying for New England states:

- Solar hop drying should be feasible for New England conditions.
- Testing should be conducted to define adjustments to operating conditions and design parameters to account for lower incident solar radiation , cloudier and lower temperature conditions compared to Denver, CO

Conclusions: Solar Hop Drying for Small Growers

- Solar hop drying can be conducted cost effectively in solar conditions of Colorado with drying times of 6 to 20 hours achievable under reasonable solar radiation; should be possible in many other locations with design adjustments
- Improvements in control systems should be possible using either temperature and relative humidity or dryer tray weigh cell measurements of beds of hops to track drying progress and completion
 - Favorable operating temperatures of 110 to 130 F for solar drying are easily obtained with a hot air plenum system of a greenhouse which can reach -180+ °F a peak solar conditions
 - Drying duration for Colorado conditions in excessively cloudy or rainy conditions can extend to more than 24 hours (without added heat storage systems)

Conclusions: Solar Hop Drying for Small Growers

- Drying after sunset could be improved by use of a solar heat storage battery, such as soil heat storage or a solar hot water collector system
- Drying after sunset with stored heat should decrease significantly the total drying time to make the dryer available for sequential daily batches
- Design operating conditions are recommended to be:
 - operate at drying air inlet conditions of less than 130 F
 - air velocities depend upon hop bed depth; for shallow bed depths of less than 6 inches air velocity is recommended to be less than 0.15 -0.2 m/s (to prevent lofting, bed blow outs, & damage to hops)

Recommendations for Solar Hop Dryer Improvements

- Further research is recommended to develop small scale counter-current moving bed systems for greater thermal efficiency, quicker drying times, and more uniform moisture content in finished hops

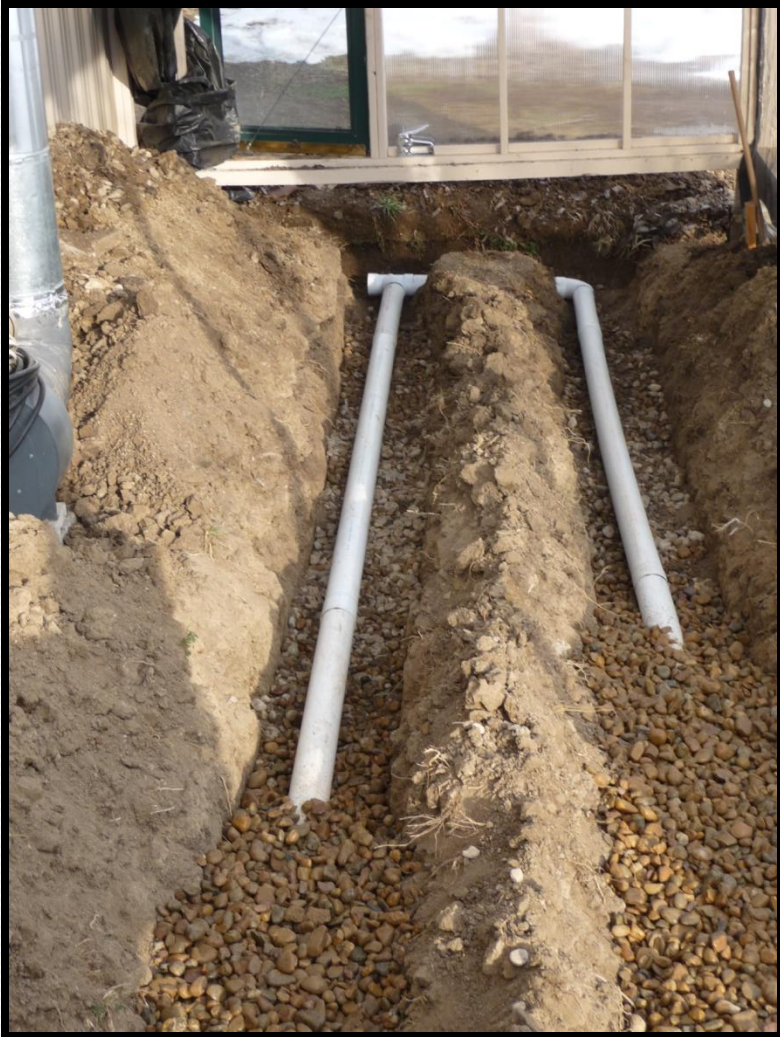
Further development of heat storage systems for use at night to shorten drying duration is recommended

Computer controls are recommended to monitor drying conditions and define adjustments of air velocity and bed inlet temperatures as drying progresses

Much more evaluation of the collected drying data for correlations and engineering parameter development is in order.

Next steps at Andrews Farm:

Completing solar greenhouse heat storage soil battery.



Celebrating fresh hopped “Wild Thing” ale at the Dam Brewery with brewmaster Corey !



**Dam Brewery
slogan:**

***“Get your own
Dam Beer”***

My slogan:

***“Beards are the
secret to good
hops and brews.”***

Good reasons to have a Harvest & Local Brews Party !



**with special thanks to Mother Nature who does
99.99999% of the real creative work!**



Richard Andrews, Hops Manager
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6803 Jay Road, Boulder, CO 80301
303 - 499 - 3031
rich@zeoponix.com



Supplemental slides follow;
not part of main presentation.
Do not reproduce for handouts.

Solar Hop Drying Test Data – Test # 11-6, Sept 11, 2011

Test conditions summary:

one drying tray

3 to 4 inch (8 to 10 cm) deep hops in tray

dryer inlet temp range: 100 to 120 °F (38 to 49 C)

drying only day time; with fan on continuously

start drying at 10:30 hours; stop drying at 18:00 hours

total drying time: ~6.5 to 7 hours to reach 10% moisture

weather, excellent solar radiation 98% of potential clear skies,
somewhat cool 70 to 83 F, dry 16 to 35% relative humidity

Test No. 11-6 -- Example of Daytime Only Solar Drying

Temperatures in Hop Dryer System, °F

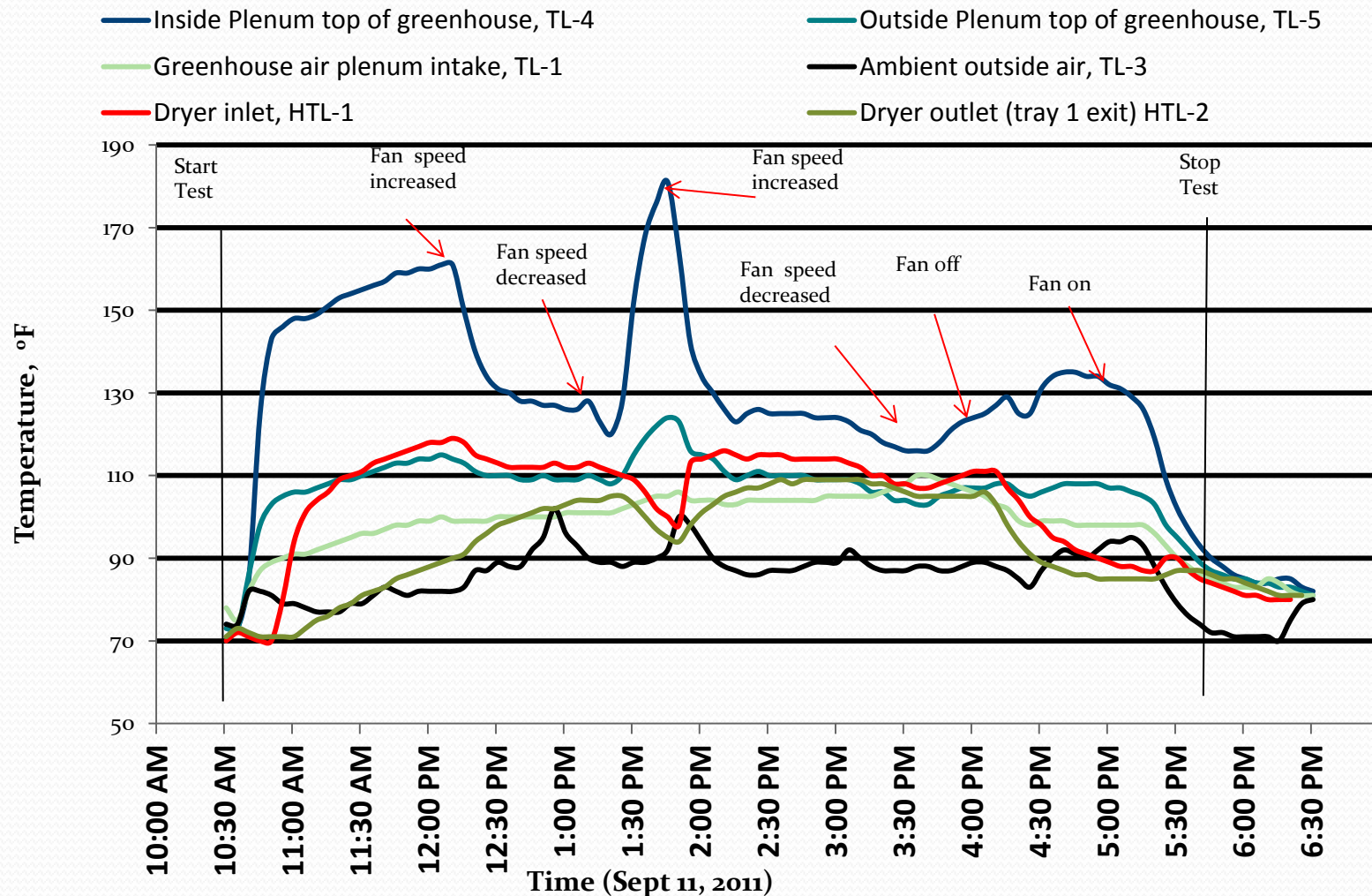
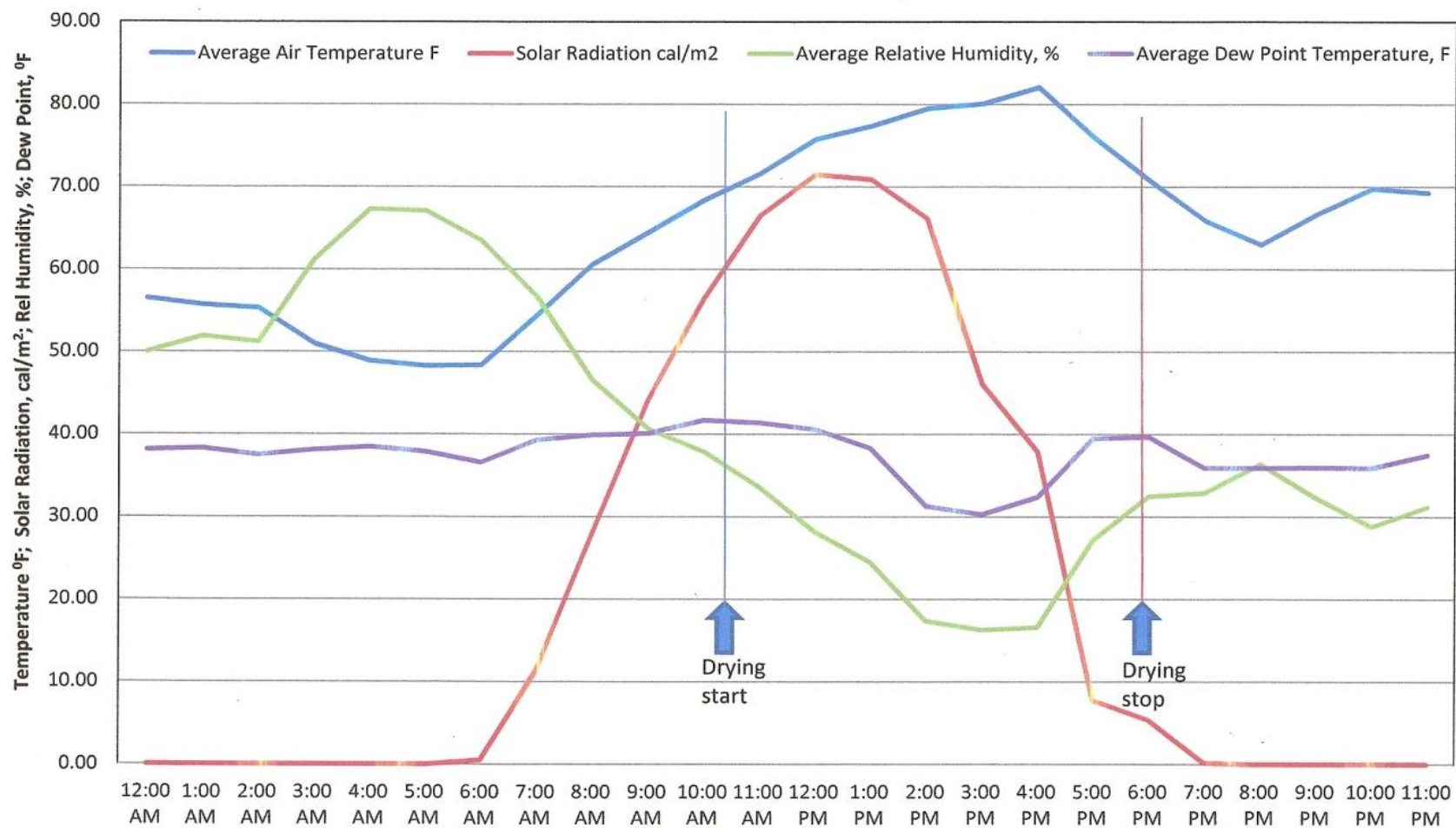


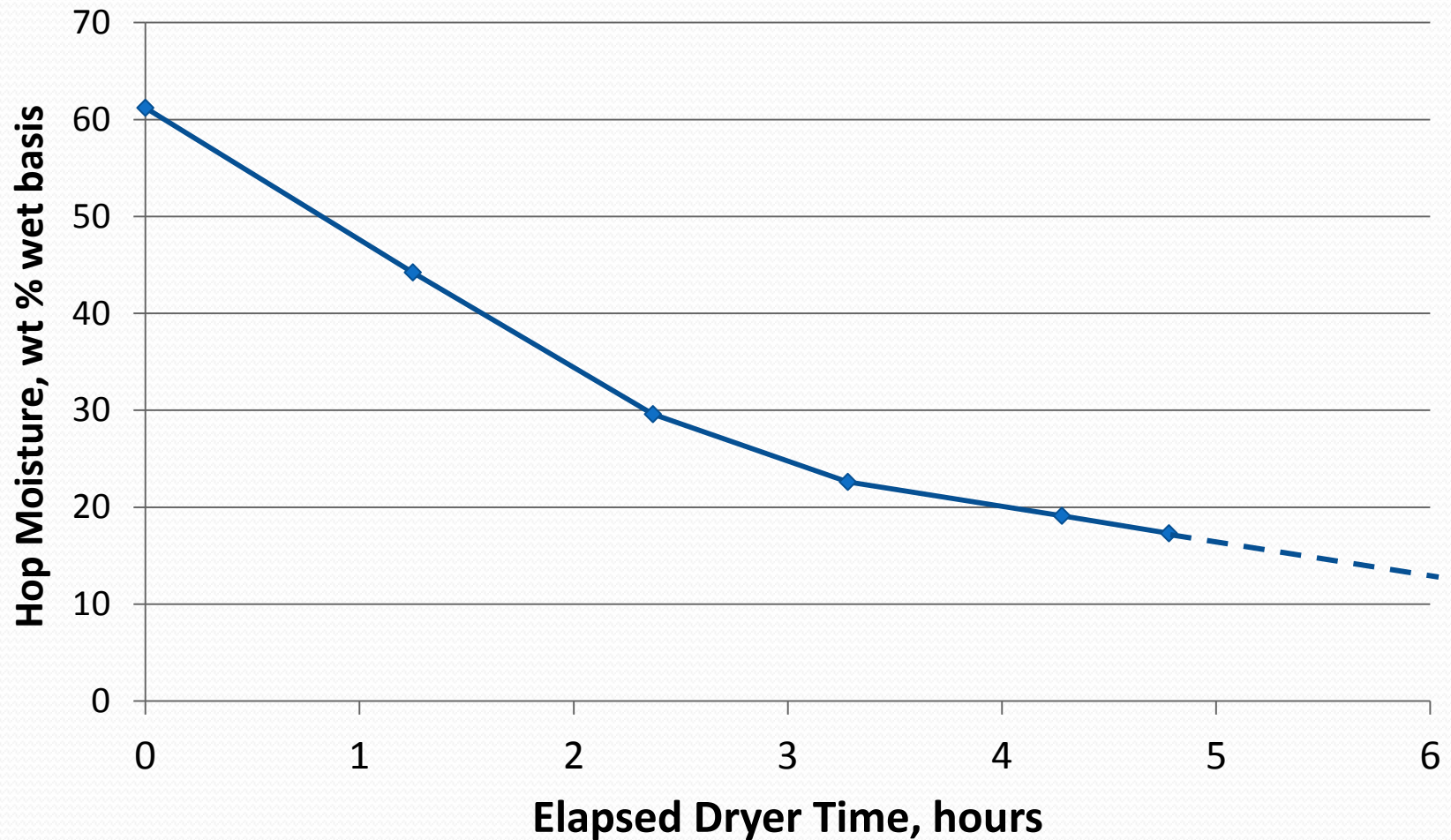
Fig. 11 - Hop Drying Test No. 6 - Sept 11, 2011
NCWCD Ambient Weather Data



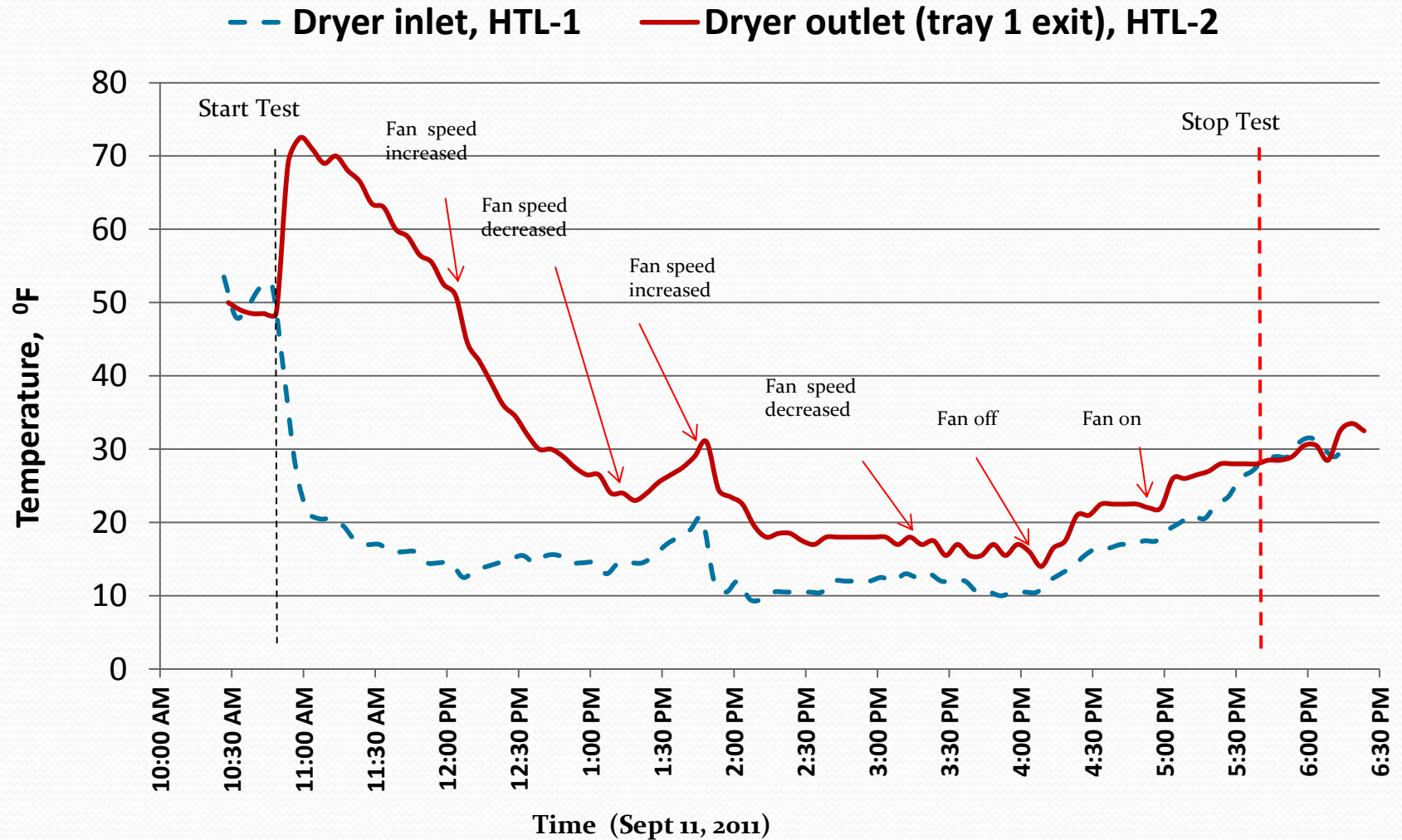
Data source: Northern Colorado Water Conservancy District, Boulder NW station, hourly readings

Hop Moisture Drying Curve

Solar Hop Drying Test No. 11-6, Sept 11, 2011



Test No. 11-6 Relative Humidity in Hop Dryer System



Solar Hop Drying Test Data – Test # 11-7, Sept 13-17, 2011

Test conditions summary:

three drying trays; two stacks

3 to 4 inch (8 to 10 cm) deep hops in trays

dryer inlet temp range: 1st and 2nd days 65 to 80 °F (18 to 27 C)

3rd day 75 to 90 F (24 to 32 C); 4th day 90 to 110 F (32 to 43 C)

drying with fan on only during daytime

start drying at 17:00 hours, 1st day; stop drying at 12:00 ,4th day

total drying time: ~26 hours with fan on; 89 hours total elapsed
time to reach 10% moisture

weather: generally poor, with rain and overcast skies for first two
days ~28 % of potential solar radiation, 80 to 95% RH; cool and
~84% of solar potential for last two days with 35 to 55% RH

Test No. 11.7 Example of Poor Solar Drying Conditions

Temperatures in Hop Dryer System, °F

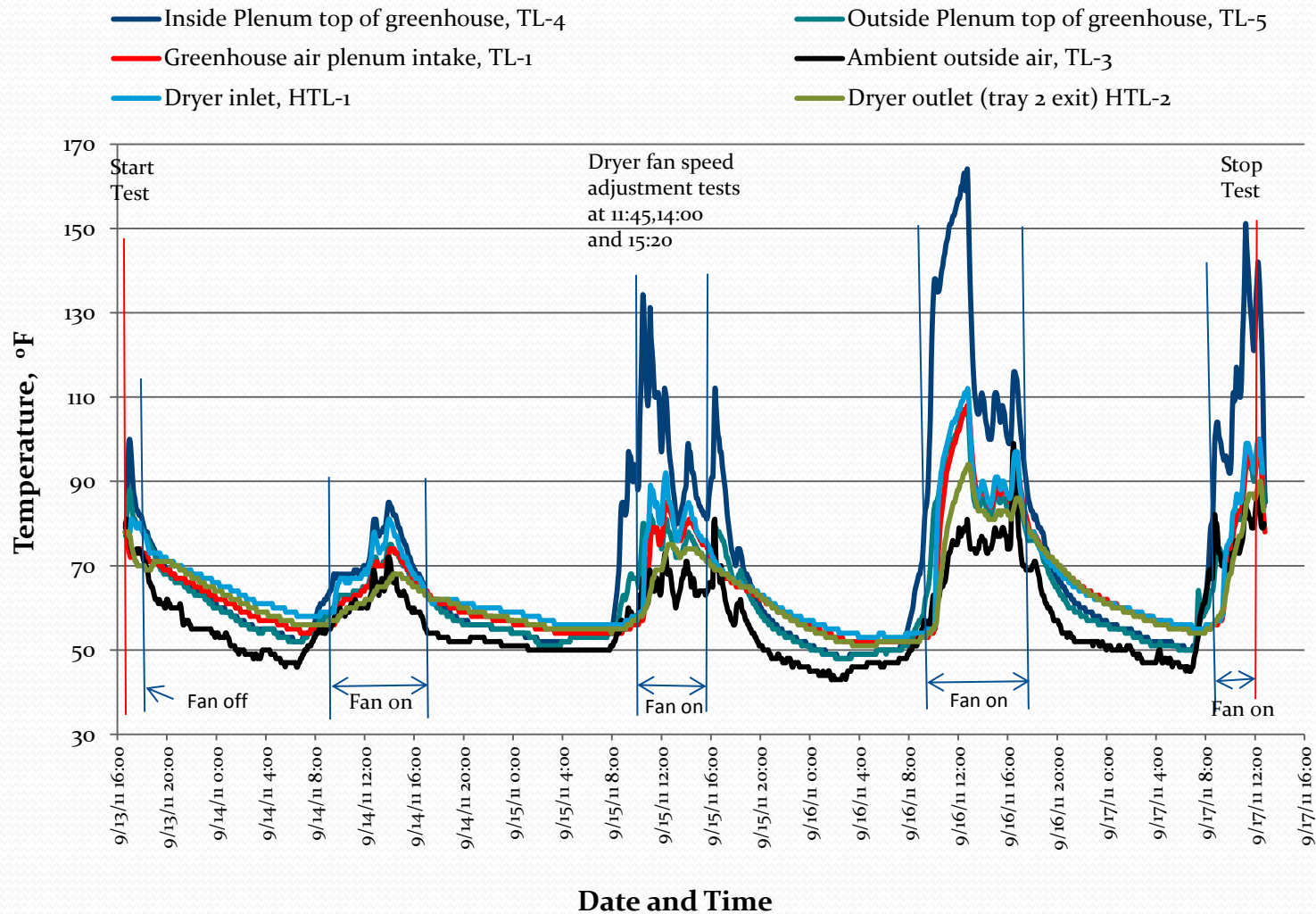
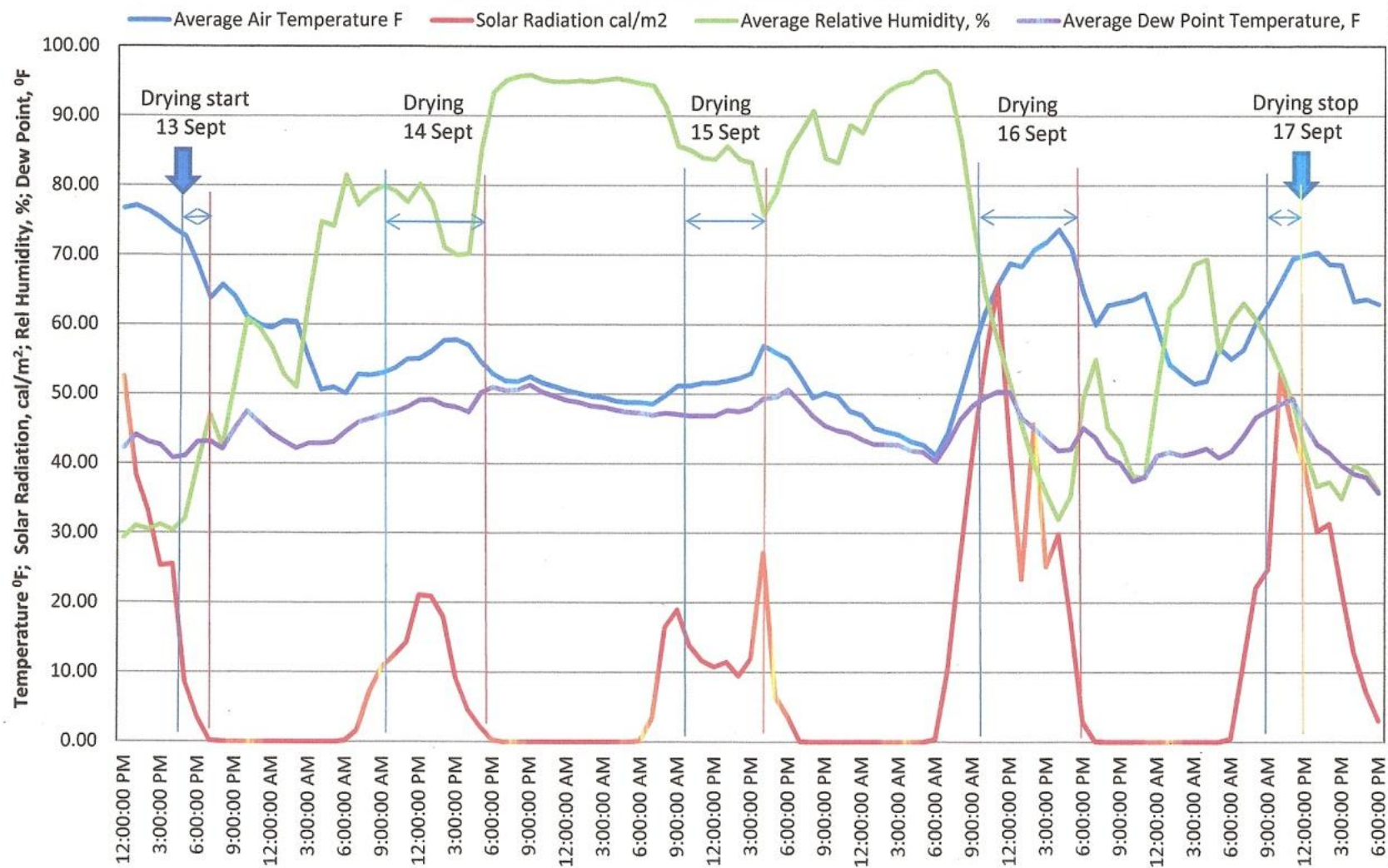
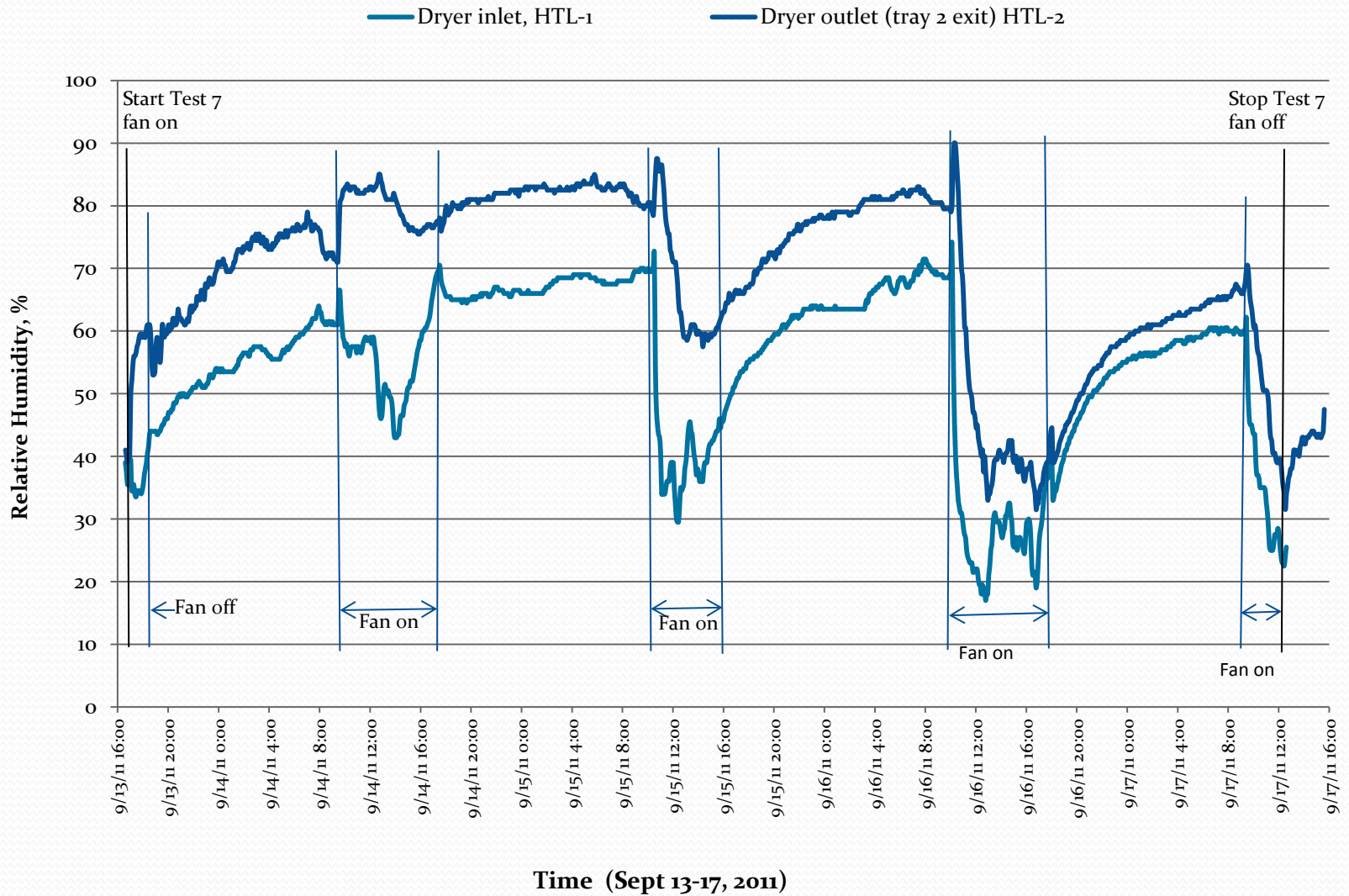


Fig 12 - Drying Test No. 7 - Sept 13-17, 2011
NCWCD Ambient Weather Data



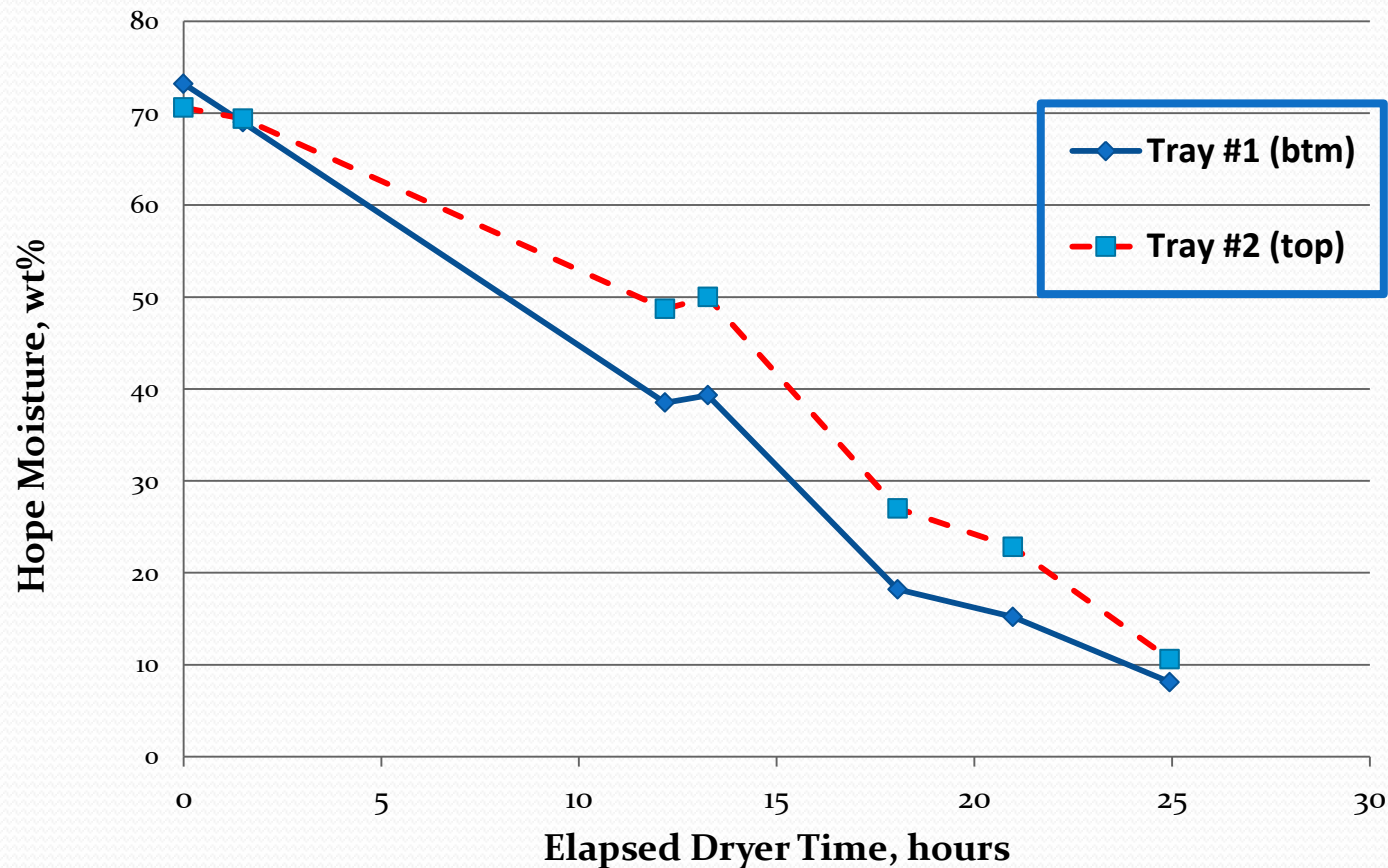
Data source: Northern Colorado Water Conservancy District, Boulder NW station, hourly readings

Test No. 11-7 Relative Humidity in Hop Dryer System %

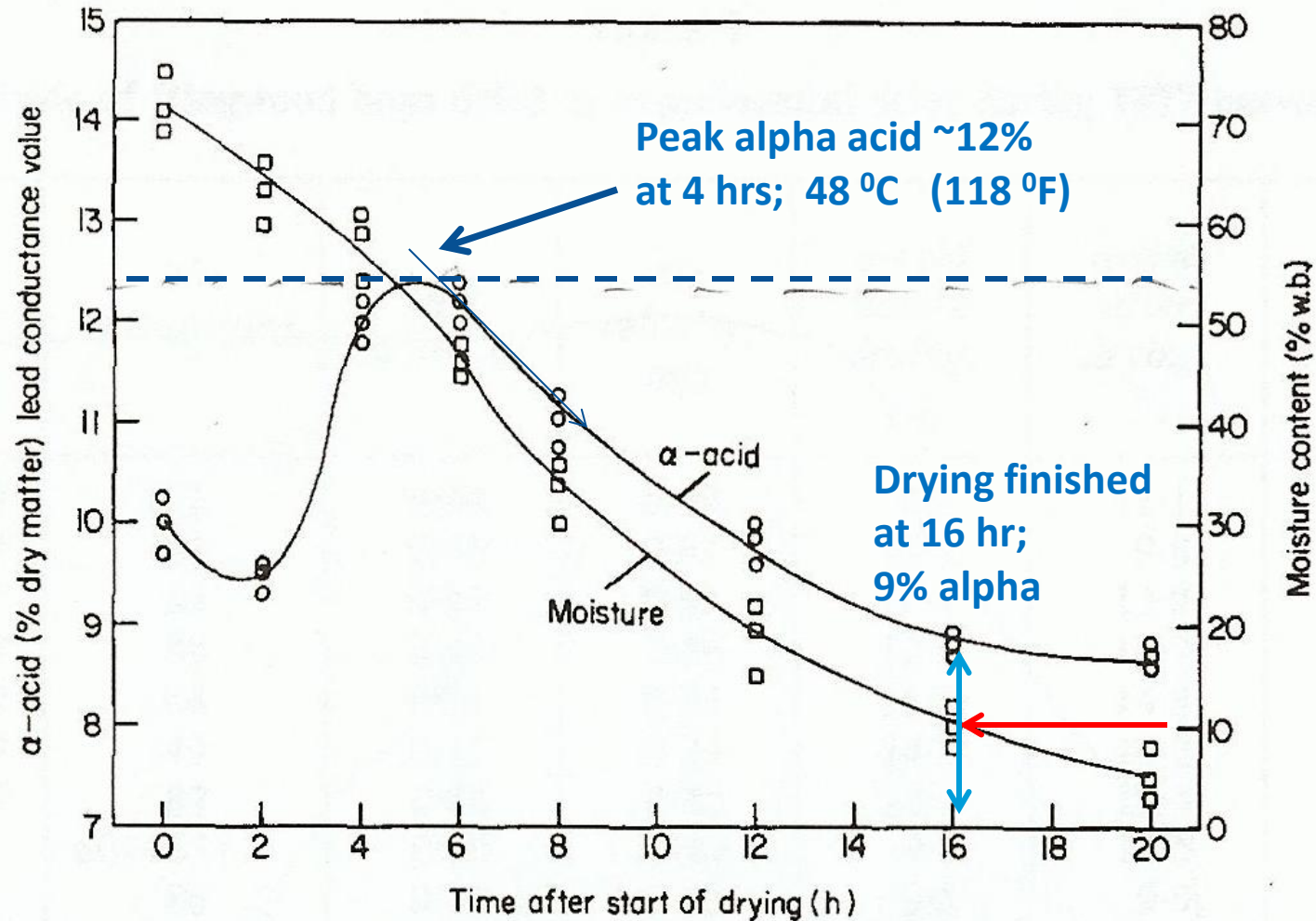


Hop Moisture Drying Curve

Solar Hop Drying Test No. 11-7, Sept 13-17, 2011



Note: Dryer time only includes times when fan was operating.
Actual total drying time for this test was approximately 3.9 days.



. Typical lead conductance value–time curve, Pride of Ringwood hops at 48°C

Note peak alpha acid before drying completed at the arrow location, approximately 4 hours at 48 C.

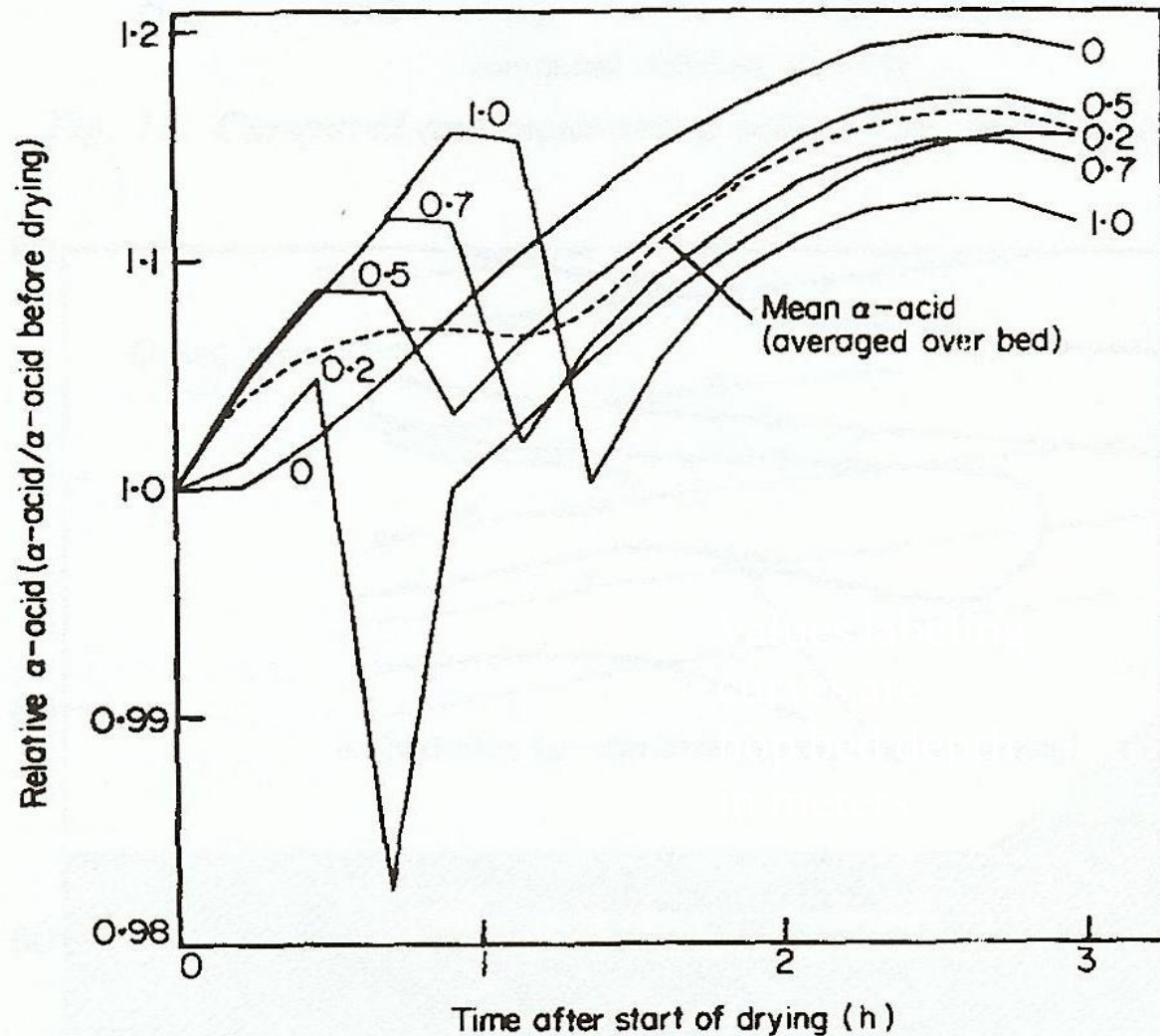
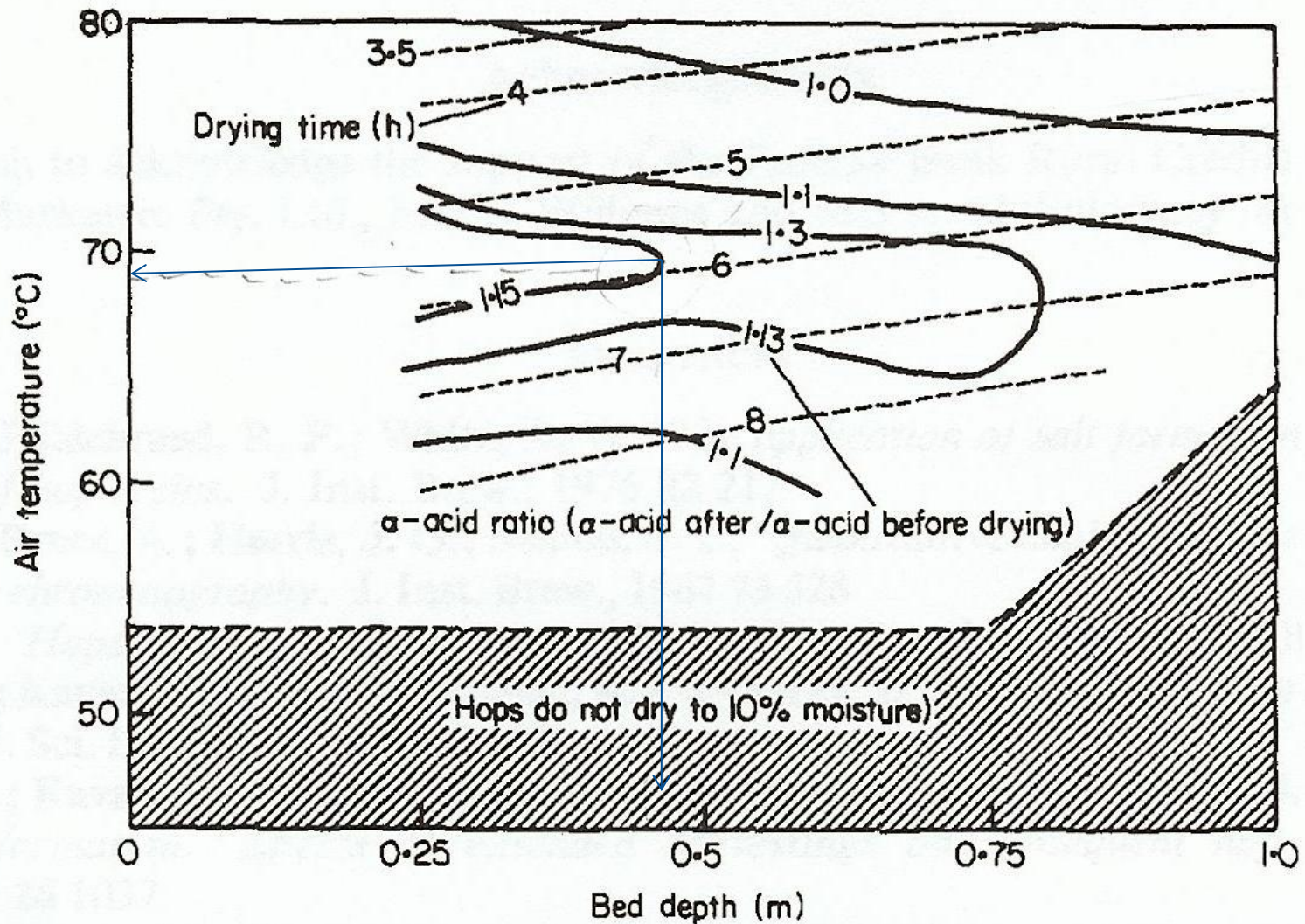


Fig. 12. Computed α -acid variations, Run 1. 1977

Variation in relative alpha acid by depth in hop layer



Equal alpha acid contours and drying times

Ref: Doe and Menary, 1979, J. Agri. Engr Res. 24, 233-249.

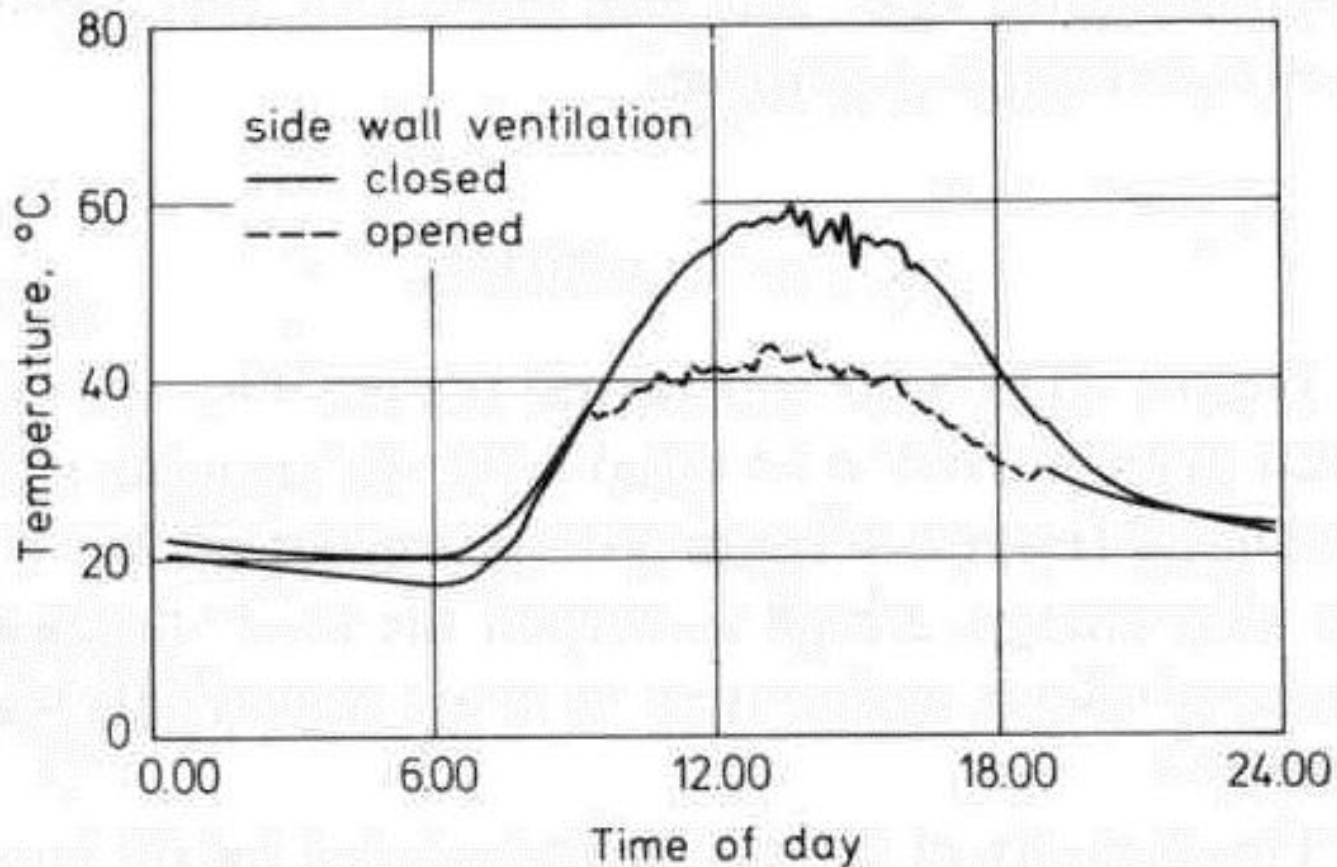


Fig. 6. Influence of the ratio of circulating air on the drying temperature vs time of day.

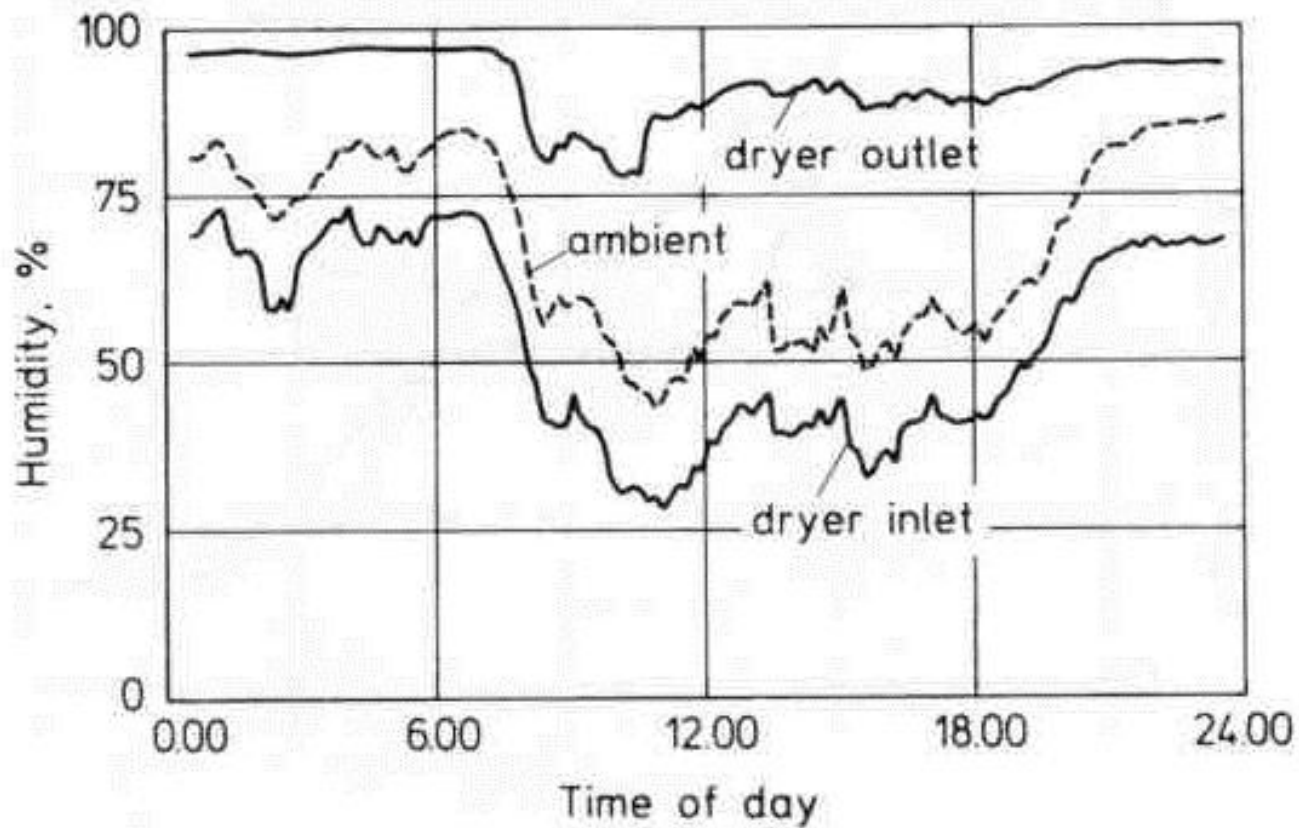


Fig. 8. Humidity of drying air, exhaust air and ambient vs time of day.

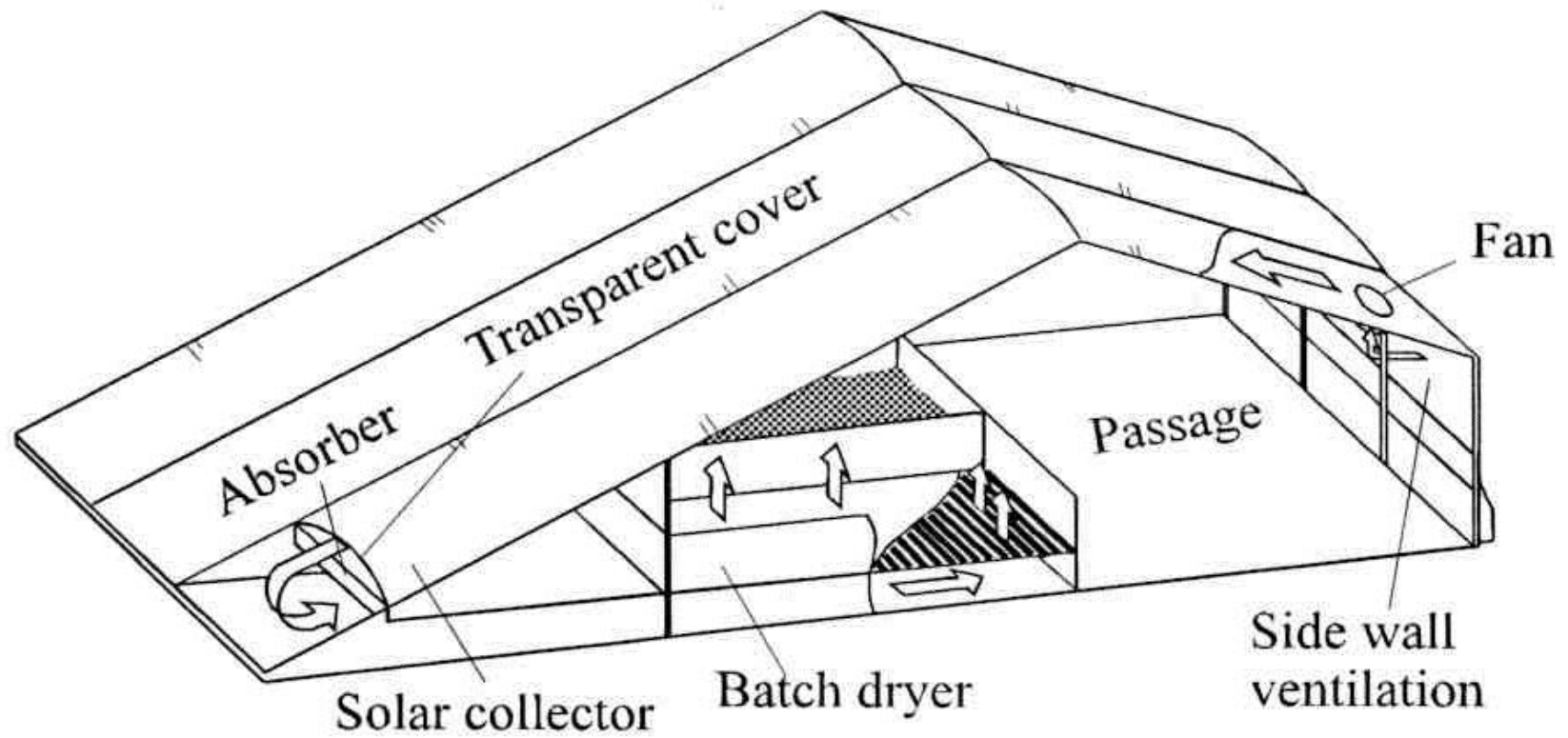


Fig. 1 Experimental solar dryer – made of air bubble foil

Table 2 Content of active ingredients in solar and conventional (small sample in a dark draughty place) dried Backa hops

Height of the layer	Solar				Conventional
	25 cm	55	85	115	
Ethereal oil, ml/100 g	0.22	0.32	0.32	0.33	0.32
Alpha acid, % in abs. dry matter	1.91	2.22	1.84	1.94	2.00
Mirzen content in ethereal oil, %	14.46	9.33	17.53	5.16	10.60
Humulen content in ethereal oil, %	48.22	51.09	43.86	53.44	49.40
Betakariophilen cont. in ethereal. oil, %	14.00	14.82	12.38	15.62	14.33



Optimal hop depth judged by Tesic to be 55 cm (22 in) based on optimal chemical quality of dried hops

Table 2. Capacity and energy consumption for mint, sage and hops

		Mint	Sage	Hops
Bulk depth	m	0.40	0.60	0.50
Bulk density	kg/m ³	60	35	100
Load per box	kg	250	200	500
Drying time	d	4	3	3
Throughput				
wet material	kg/d	360	400	1000
dry material	kg/d	80	170	250
Evaporated water	kg/d	280	230	750
Specific energy				
Consumption				
per kg water	kWh/kg	0.27	0.33	0.10
per kg crude drug	kWh/kg	0.93	0.44	0.30

Bed dimensions are 2 m x 2 m or cross section area of 4 m² per drying box

Ref: Muller et al

Table 3. Percentage of active ingredients of conventional and solar dried mint, sage and hops

			Conventional dried	Solar dried
Mint				
ethereal oil	ml/100 g		2.5	3.5
chlorophyll a	%		1.38	1.92
chlorophyll b	%		0.69	0.85
carotinoid	%		0.55	0.73
Sage				
ethereal oil	ml/100 g		1.6	2.0
Hops				
ethereal oil	ml/100 g		0.96	1.66
alpha acid	%		4.52	5.89

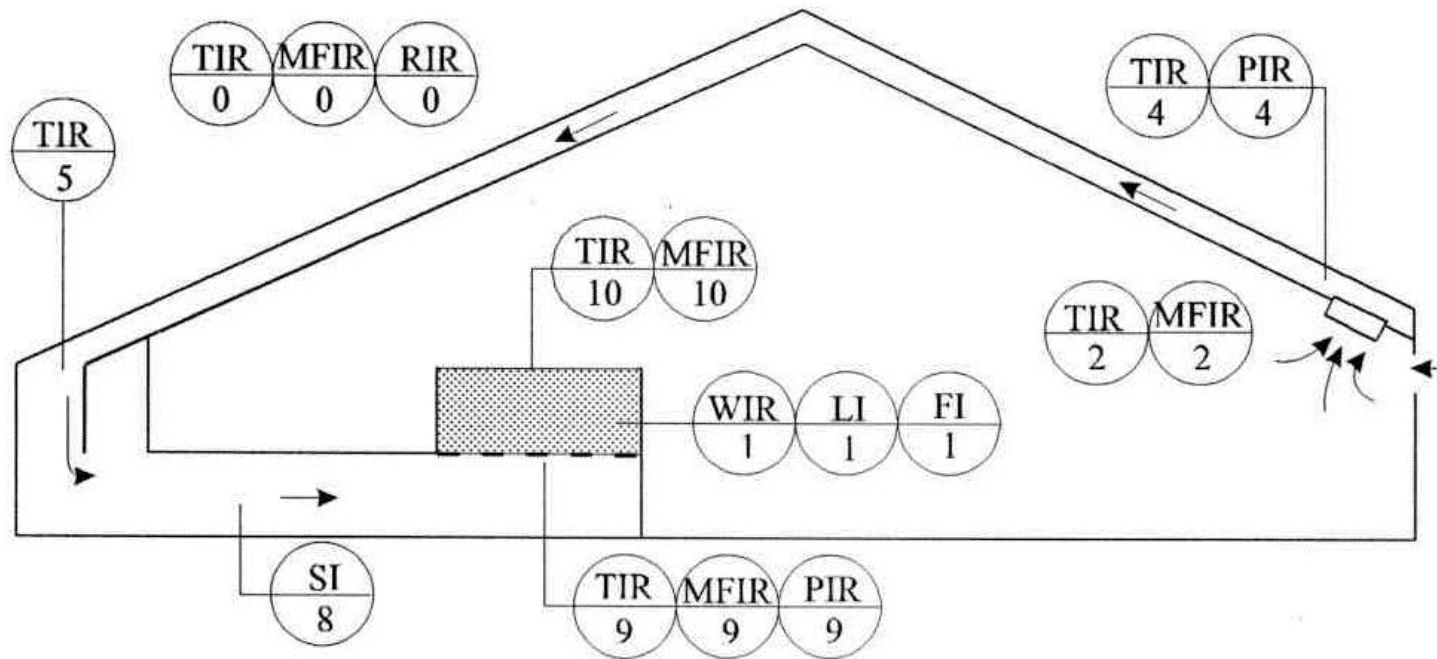


Fig. 2 Plan of measuring points

Table 1 Average data about hop's drying in the experimental solar dryer

Height of the layer, cm	25	55	85	115
Bulk density, kg/m ³				
– at the beginning	65.5	80.7	93.7	100.6
– at the end	29.5	35.0	41.5	43.5
Moisture content, %				
– at the beginning	72.6	74.3	73.3	73.7
– at the end	8.7	8.7	8.9	8.5
Duration of drying, h	42.1	49.7	102.0	130.0
Total of solar radiation energy, kWh/m ²	8.2	9.7	20.7	26.5
Average air temperature, °C				
– of the ambient	19.3	18.7	18.8	18.9
– under the box	29.1	29.0	29.5	29.0
Average air velocity in the duct, m/s	0.82	0.76	0.55	0.53
Air flow quantity, m ³ /h				
– at the beginning of drying $w = 73\%$	3140	2460	1920	1580
– average for drying all samples	3173	2500	2090	1850
Drying rate, kg/h				
– wet hops	1.94	4.14	3.42	3.56
– dried hops	0.58	1.20	1.00	1.02
– water evaporation	1.36	3.51	2.41	2.53
Electrical energy consumption, kWh/kg				
– evaporated water	0.41	0.15	0.17	0.17
– dried hops	0.94	0.37	0.42	0.44

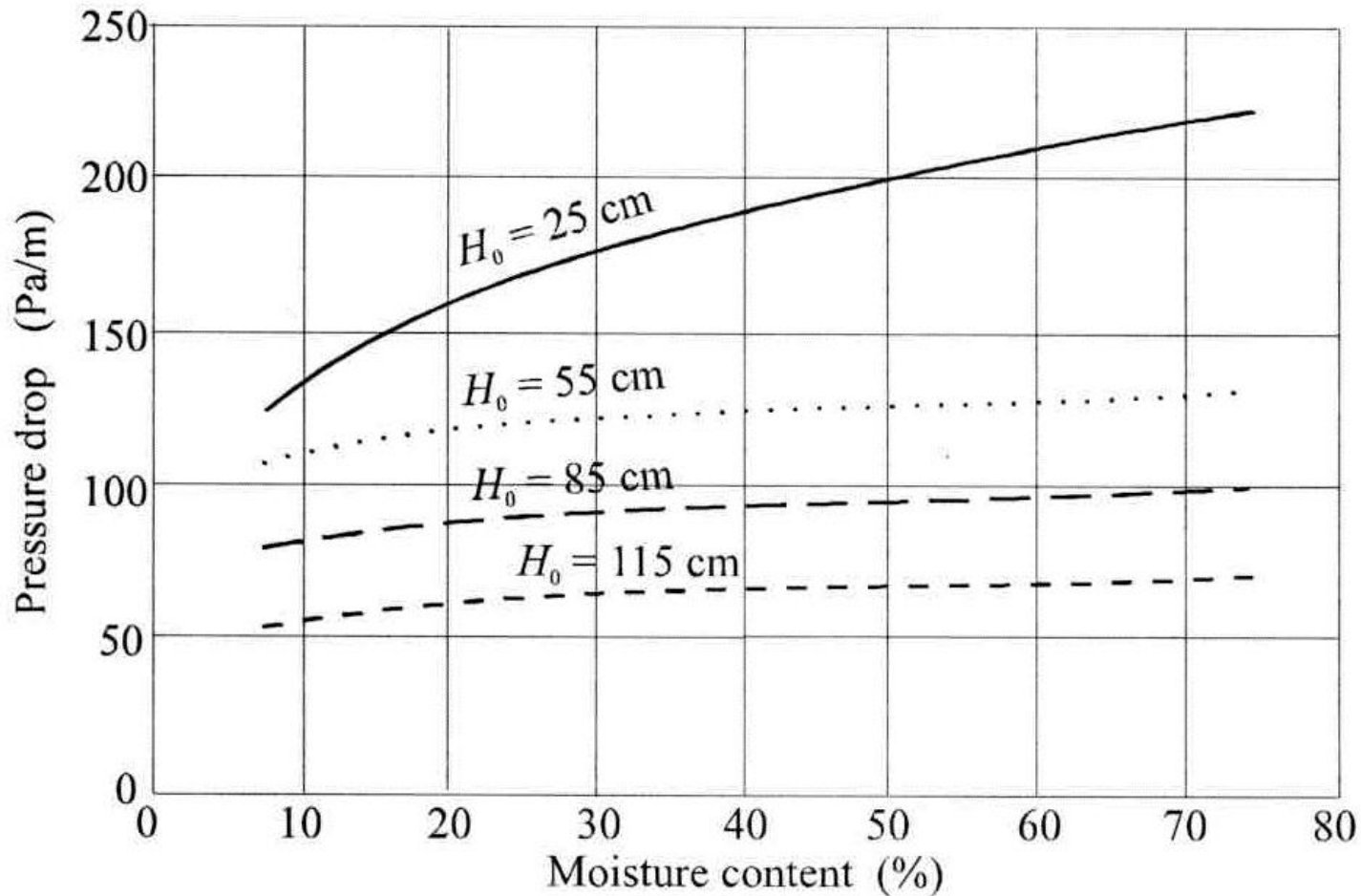


Fig. 4 Mean specific air flow resistance in hop layers of different heights during solar drying

With lower bed depth air flow resistance declines as hops dry. Consider using lower air velocities as drying proceeds to prevent bed lofting and cone shatter or excess drying.

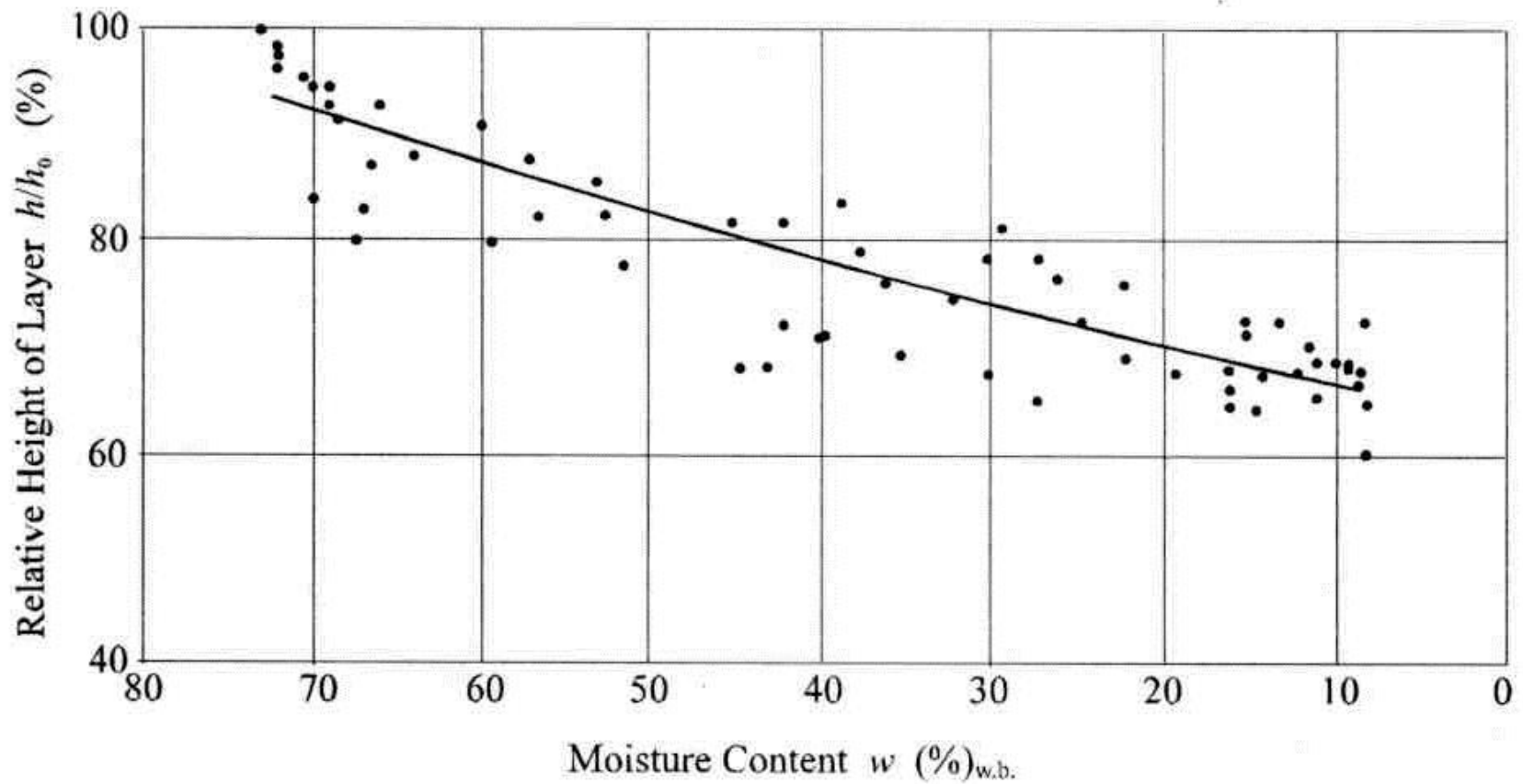


Fig. 6 Relative reduction of hops layer's initial height

Illustrates hop (bed) shrinkage with time as drying progresses.

Problems to be studied & resolved:

- Minimize drying times to maximum of one half day per batch
- Minimize hot air collector area required relative to hop dryer bed area
- Improve on uniformity of moisture in hop layers of drying bed (e.g. hop turning, moving bed, staged thin beds, counter-current hops flow to air flow, etc.)
- Develop solar heat storage system for night time drying and shorter overall drying duration

Solar Drying Limitations and Research Needed:

- Need to determine optimal air velocity in collectors, collector designs, and hop drying beds geometry for best heat transfer
- Need to evaluate recirculation of dryer exhaust to fresh air intake ratio for maximum drying energy efficiency; recycled humid air a possible advantage
- Need to determine optimal combination of air velocity, hop depth, recirculation to achieve shortest drying time and to maintain highest hop quality characteristics

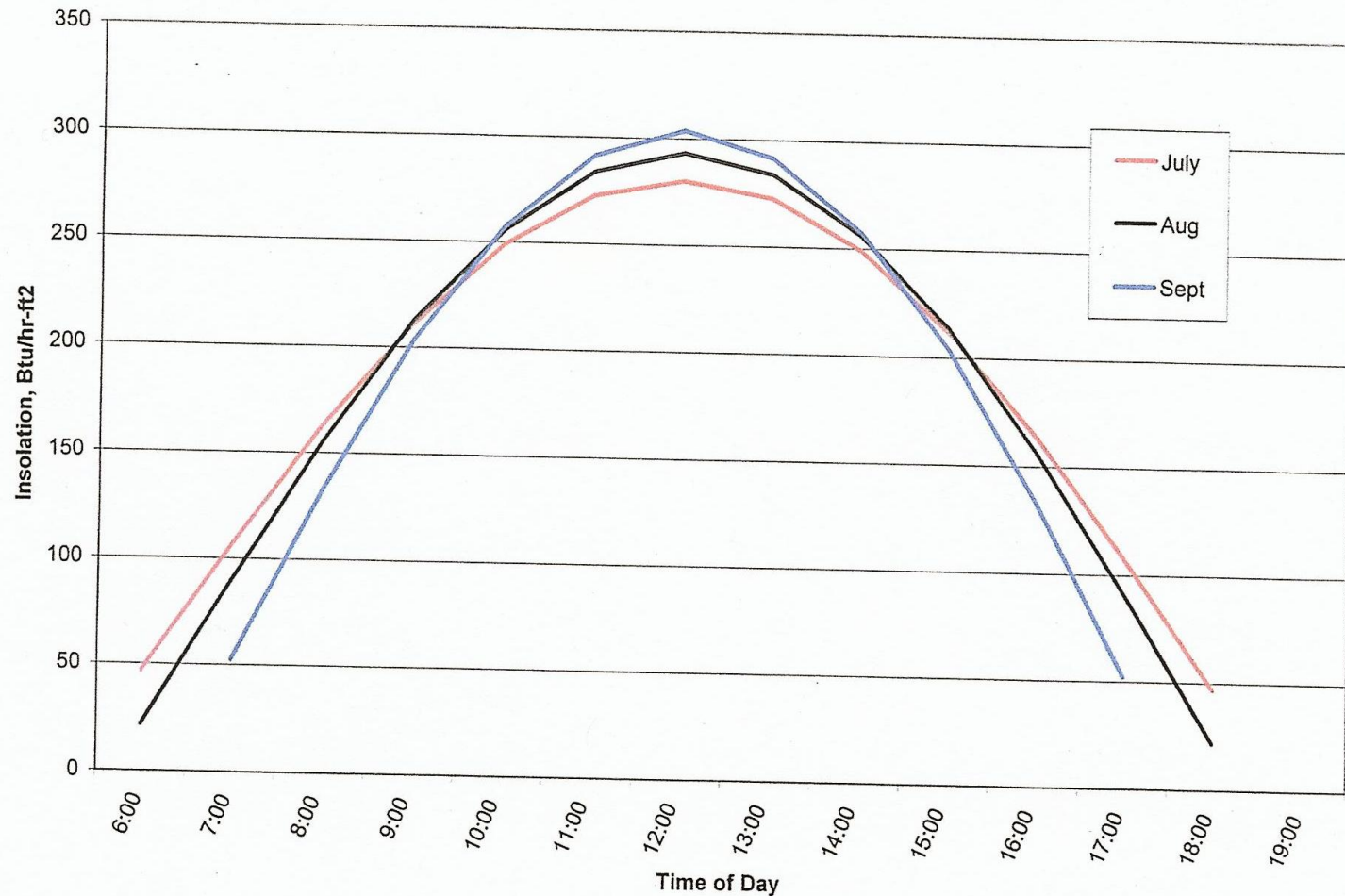
Some Gleanings from Greenhouse Hot Air Dryer System Prior Research by others:

- **Suitable operating temperatures for solar drying of 40 to 60 °C (104 to 140°F) can be achieved**
- **Drying completion may be determined by bed pressure drop measurement and/or bed shrinkage; may be able to use convergence of difference in relative humidity, bed inlet to outlet**
- **Optimal hop layer depth for this hot air system is approx. 55 cm (22 in), for suitable drying duration and hop quality**
- **Avoid extended drying periods to avoid degradation in hop alpha content.**
- **Avoid excessive drying to avoid cone shatter and poor storage quality; remember you are selling by weight so excess drying is actually less revenue also.**

More Gleanings from Greenhouse Hot Air Dryer System Prior Research:

- **Solar collector area of 344 sq feet needed for dryer bed area of 129 sq feet. (ratio of 2.7:1)**
- **Max air flow rates of about 10 to 20 cfm/sq ft of bed area; 3 to 6 cfm/sqft of collector area; depending on system design and collector efficiency**
- **Fan size is preferably variable speed and air flow to be able to tune air volume and velocity during the drying period.**
- **Dryer operating temperatures are optimal at less than 120 to 125 °F to achieve optimal alpha acid and volatile oils conditions; lower temperatures are better (some conflicting information on this)**
- **Drying should be accomplished in less than 12 hours, preferably less, to be compatible with harvest schedules and the short harvest window of hops**

Solar Insolation at 40N Latitude and 25 degree Collector Mount Angle



Diurnal Solar radiation for Boulder, Colorado
(similar to Delta County, Colorado area also)

***Don't allow no
GMO corn
'round
here !***

