CY 2012 Annual and Final Report to CSU Specialty Crop Program –
Grower Research & Education Grant (GREG)
Year Three

Research, Development and Demonstration of
Solar Hops and Herb Drying
For Small Farm Applications

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Executive Summary –

This project began in 2010 but was delayed in start up due to local permit problems to build the necessary facilities. The project began in earnest during CY 2011 with data collection completed during CY2012 hop harvest season. This report concludes the study.

During 2011, a solar hot air dryer was constructed and operated; the dryer had six drying trays in two stacks, each tray with cross section area of 14 ft$^2$ (1.3 m$^2$) and 12 in deep (30.5 cm). The hot air was collected from a plenum space between the polycarbonate twin wall glazing and a black poly plastic film attached to the underside of steel trusses at the top of a greenhouse. Inside the black plastic film was a black woven fabric shade cloth to provide a rough surface and air turbulence for better heat transfer. Total hot air plenum collector dimensions were approximately 12 ft wide x 18 ft long (3.6 x 5.4 m), for collector area of 216 ft$^2$ (19.4 m$^2$), including the arched roof and vertical side wall areas, which are 144 ft$^2$ (13 m$^2$) and 72 ft$^2$ (6.4 m$^2$), respectively. The air plenum thickness was approximately 5 inches (12.7 cm). Hot air temperatures to the dryer could be controlled by dilution air mixing using a damper intake in combination with the intake from the hot air plenum. The system was instrumented with data logging temperature and relative humidity sensors, plus sequential timed digital readout for thermocouples at numerous locations. Air velocities in ducts and through the drying beds were measured with a portable hot wire anemometer. Hop moisture measurements were made with laboratory balance (nearest 0.1 g) and laboratory oven. Photographs of the dryer and instruments are in Appendix F, as well as in the 2011 Progress report.

Seven separate drying tests were performed in 2011 under a variety of weather and operating conditions, varying air velocities, hop depths and other variables. System modifications were subsequently made to improve the blower system and the dryer tray stack and ducting. During CY-2012 an additional fourteen solar drying tests were conducted, with additional humidity instrumentation in the latter tests to better characterize the operating conditions and effects on drying rates.

Solar drying of hops was demonstrated to be effective with the only energy inputs being electricity for powering the blower to collect and route hot air into the dryer. In the case on the test site even the electricity was solar powered from photovoltaic panels on the barn roof. In effect, the system was totally solar energy powered.

Prior to beginning the project, the existing literature was retrieved and used to guide the design of the systems. Such design factors as the range of suitable hop depth in drying beds, air velocities through the beds, and preferred drying air temperatures and humidity were obtained from literature to guide the ranges to be examined in solar tests. The effect of these design and operating parameters on hop quality and duration of drying episodes were considered.

During the 2011 season, the weather was variable with some excellent solar conditions as well as some periods of extended cloudiness and precipitation. During good solar conditions, drying of
batches could be accomplished in a single day, whereas during the rainy and cloudy period, drying extended over multiple days to achieve the desired 10 wt% wet basis moisture.

During the 2012 season, the weather was quite favorable with no significant adverse solar drying days. All drying was accomplished between 6 to 16 hours total duration in the dryer. Most of the drying tests that extended to the 16 hour duration were commenced at the end of daylight hop picking campaigns and often completed by mid day to early afternoon the following day.

Typical range of operating conditions during these 2011-2012 tests for solar hot air drying were:

- High air temperatures in solar collectors: 120 to 180 °F
- Diluted drying air entrance temperatures: 100 to 130 °F (38 to 54 °C)
- Air velocities thru drying beds: 0.02 to 0.14 m/sec (0.07 to 0.46 ft/sec)
- Hop depths in drying beds: 2.5 to 5.5 inches (6.4 to 14 cm)
- Drying rates during night hours: 0.02 to 0.03 lb H₂O removed/lb dry hops/hr
- Drying rates during day hours: 0.05 to 0.07 lb H₂O removed/lb dry hops/hr

Possible controls to utilize in operating a solar dryer were investigated. It was determined that during the final stages of dryer operation that the difference between drying bed inlet and outlet relative humidity may be able to be used to determine the optimal 10 wt% hop moisture end point.

The relatively lower rate of drying during nighttime hours when only ambient air is circulated through the hop beds extends the total elapsed drying time. This may be able to be improved by utilizing solar heat storage such as may be possible with a hot water solar system. Due to insufficient available funds under the grant, studies on the use of solar hot water and heat storage systems to enhance drying during night time or during poor solar days were not conducted.

Conclusions are that hot air solar drying with the greenhouse solar collection system can be effective for hops, certainly in the solar conditions during most seasons in NE Colorado. While it is desirable to pick hops after morning dew has evaporated, that necessarily means that solar hop drying would not be started until mid day or later. The peak solar radiation hours to obtain the shortest drying times are between 9 am and about 4 pm, so adjusting picking schedules should seek to accommodate that window to the extent possible. However, these tests demonstrated that successful solar drying can be achieved when only ambient air is circulated through hop beds overnight and drying finished the following day during good solar conditions.

Recommendations include developing an instrumental means to determine the optimal time (hop moisture) to conclude a drying session; to prevent over or under drying. A digital load cell for the drying trays would be one approach. From these tests it appears that using convergence of relative humidity (RH) at the inlet and outlet of drying beds may guide end point determination and real time RH measurements could be automated to shut off drying fans at the optimal time and signal unloading to cool down and conditioning prior to packaging. Further investigation is recommended into solar hot water and heat storage systems to allow extension of drying into evening and night hours. An air tight dryer and ducting system would be an improvement (ours was not) and could accelerate drying by
utilizing the higher plenum temperatures that were demonstrated to be achievable. A system that progressively moves hops through a dryer countercurrent to the hot air flow is likely optimal for shortest drying duration (like the multi-deck louvered floor systems). Some other investigators have proposed “modified air flow” drying in which air velocity is changed depending upon the stage of drying; that should be investigated for solar drying systems for further optimization. The effects of drying temperatures, RHs, and re-circulating air on hop quality, such as alpha/beta acid and hop storage index were not investigated in this study and would be reasonable areas to enhance solar systems.

Background —

Colorado has over the last few decades become the number one brewing state in the USA, with two very large brewers, and more than 140 micro and craft brewers some of which have grown to top ten national output capacity. The local Colorado hop growing capacity has been slowly developing over the last five to six years, but not on pace with the local brewer demand. Typical hop farms in Colorado are less than 10 to 20 acres, several much smaller at 1 to 2 acres. Existing hops growing in the USA is predominated by a small number of very large operations, averaging 800 acres per hop ranch, most in Washington, Oregon and Idaho. Hops drying and processing is also very large scale and centralized with only a few corporations. The scale of the equipment and methods used by these large operations is not applicable to or affordable by small farmers, such as the infant hops industry arising in Colorado. Many of the Colorado growers are organic. There is very limited organic hops production in the USA, so this may be a niche that Colorado growers can capture.

Hop drying currently done by the large corporate processors consists almost universally of deep bed batch drying operations operating at high temperatures (150° to 160° F) using natural gas, propane, or fuel/diesel oil, often in direct fired dryers (the kilns are known traditionally as oast houses). This technology while well established is not considered optimal from a product quality view, has a significant carbon footprint, and is costly in fuel. A main motivator seems to be speed and expediency to handle the hops during the short harvest season. Excessively high temperatures can be detrimental to quality due to loss of the valued volatile oils and chemicals in the hops that are important for brewing and medicinal uses. The direct flue gas contact with hops is also a possible source of undesirable fuel derived contaminants to the product. Solar drying methods are preferred to save energy costs, lower greenhouse gas emissions, operate at lower temperatures, and produce higher quality safer products, particularly important to organic growers of Colorado.

Hops growing has a relatively high entry cost per acre, typically from $9,000 to $13,000 per acre for plant rhizome stock, trellising and irrigation systems. Harvesting equipment (pickers) and drying-packaging using conventional equipment is quite expensive, the least cost smaller scale pickers being from $30,000 (used) to more than $400,000. Some very small scale home built pickers can range from $5,000 to $20,000. Conventional deep bed batch dryers can cost in the range of $30,000 to $100,000 or more, depending upon scale and not including buildings to house this equipment.
Existing technology used in the USA hop drying business while functional, is dated and relies on significant inputs of fossil fuels for drying the harvested hops. Drying of hops requires removal of field harvest wet moisture content of approximately 65 to 80% by weight down to the standard of 8% to 11% by weight, optimal at 10% wet basis. Conventional direct fired batch dryers with bed depths of about 36 to 40 inches (91 to 102 cm) require from 8 to 14 hours drying time with air flow rates ranging from 30 to 400 cfm/ft² bed area, typical 50 cfm/ft². Heat rates are reportedly around 2960 Btu/hr-ft² of bed area (Kranzler 1981). For a typical 32 ft x 32 ft drying bed which can produce approximately 3800 pounds of dry hops per batch, the energy delivered is approximately 3 million Btu/hr for an assumed 14 hour drying cycle. Drying fuel input energy is on the order of 11,200 Btu per pound of dry hops. Based on propane firing, which is the expected fuel that would be used by Colorado hop growers, this equates to about $0.24 to $0.29 per pound of dry hops (10-11% moisture basis) (at propane price of $1.95 to $2.50/gal, 91,690 Btu/gal).

Given the high solar insolation rate during the harvest season (mid August-mid September) in the hops growing areas of Colorado, currently mostly in the north Front Range and Gunnison-Uncompaghre River valley, solar drying technology is expected to be very successful, giving small Colorado hop growers a competitive quality advantage to help offset their small scale disadvantages relative to the large corporate farms of the Pacific Northwest. Average solar insolation during daylight hours in hop drying season (Aug-Sept) is approximately 2115 Btu/day-ft² (240 MJ/m²-day)(5.74 mcal/m2/day) for the Denver and Tri-River areas at 25° collector angle (Duff, Beckman 1991). See Figure 1 for typical daily solar insolation at 40° N and for a near optimal late summer collector angle 25°.

![Solar Insolation at 40N Latitude and 25 degree Collector Mount Angle](image)

Figure 1 – Boulder, Colorado Solar Radiation, August-September
For hop growers in other regions, a careful examination of the transferability of solar drying technology is necessary, ensuring that the solar radiation during the harvest season is suitable to achieve results comparable to those demonstrated in this and other studies.

Solar hop drying has the potential to reduce operating costs as well as improve product quality. Capital costs for systems may also be lower than more conventional fossil fuel fired systems. Solar drying is also more compatible with overall sustainable and organic farming practices, the direction for the future.

**Solar Hop Drying Industry Experience and Literature**

Hops quality and preserving the alpha and beta acids, polyphenols, antioxidant characteristics, and volatile oil content are very important price determinants on hops, perhaps more so for medicinal customers than brewers. Hop pricing for brewers is often based upon alpha acid content, not just variety and dry weight. Evidence from the literature indicates that the higher the drying temperature and duration, the lower the alpha acid content in hops. Burgess (1931) noted that higher temperatures (range from 80° to over 200° F) generally depress alpha acid; Burgess (1964) indicated that hop quality was reduced by constant drying temperatures above 140° F (40° C). He also noted that extended duration low temperature ambient air drying (~ 65° F) was not beneficial and resulted in lower alpha acid. Henderson and Miller (1974) report definite declines in alpha acid at temperatures above 150° F but they unfortunately did not evaluate lower temperatures.

Over-drying to lower than 8% moisture is also a concern which can result in hop bract shattering and potential loss of the lupulin content during handling. Henderson and Miller (1974) identify 10 to 11% final equilibrated moisture as optimal for storage, but any higher can lead to in bale storage decay or molding. Krofta et al (2008) observe <5% losses of antioxidant and polyphenol properties with drying at 50° to 60° C; although it is not clear that lower temperature drying would prevent this. Roßbauer and Munsterer (2009) discuss optimization of hop drying and conditioning to safeguard hop quality and advocate use of humidity controls to determine end points of drying. Colin Oldham (2008), a New Zealand organic hop grower, states he achieves significantly improved alpha acid retention using coal fired boiler hot water exchanged to indirectly heat air in an updraft four stage multi-deck dryer with humidity controls for determination of drying completion, when compared to conventional batch deep bed drying. Zeisig (1970) and Bloxham (1980) examined adjusting air flow relative to effects on hop quality. Higher air flows and temperatures can be used with fresh heavier hops (~5 lb/ft²) but are reduced as hops decrease in density and moisture (1 lb/ft³) upon drying. Thompson, Stone and Kranzler (1985) studied drying methods varying the temperatures and air flows at different stages in drying (Modified Air Flow or MAF), achieving shorter total drying time while preserving hop quality.

Kranzler and Zimmerman (1979) and Kranzler (1981) studied a solar assisted air preheating hop dryer in conventional deep batch bed drying. Muller et al (1989) examined use of greenhouse-type solar dryer for hops and other herbs; effectively drying hops and herbs with solar heat alone in an extended 3-4 day drying period, and noting up to 40% higher active ingredients compared to conventional drying.
Other relevant published work, as yet not retrieved, (Tesic (1994, 1998), Sabo (1994), Abengoza (2009), Doe (1975, 1979)) also deals with solar drying of herbs and hops. Miller (1985) recommends drying temperatures from 85° to 120° F (29° to 49° C) for most medicinal herbs to preserve the important properties and specifically calls for this range for hops. Whitten (1997) recommends not exceeding 95°F (35° C) for hops drying when the product is for medicinal herb purposes, and similar maximum temperatures for most herbs. He does note that for beer brewing hops, higher temperatures may be acceptable, even as high as 176°F (80°C) "in order to destroy a certain enzyme" while not affecting the bittering character. Whitten provides several possible solar dryer configurations. More literature research is needed to survey the field of studies and opinion and to determine optimum temperature ranges, but the tendency in most literature is that lower ranges than are conventionally used are preferred.

From Krenzler (1981), a simple home-made hot air collector in a solar assisted hop dryer achieved approximately 520 to 570 Btu/ft²-day (5.9 to 6.5 MJ/m²-day)(1.4 to 1.55 Mcal/m²-day), not optimally mounted or insulated. Commercial sub-optimal vertical wall mount hot air collectors advertise rates of approximately 200 to 250 Btu/ft²-day (2.3 to 2.8 MJ/m²-day)(0.55 to 0.67 Mcal/m²-day). More optimal designs and mounting orientations should achieve higher heat collection efficiency. Air flow rates, absorber and glazing materials, insulation and mount angle for hot air collectors are critical to efficient system design to maximize energy transfer.

Solar drying technology also has the advantage of being clean and avoids the potential for contamination from fossil fuel and flue gas contaminants. The organic hops growers in New Zealand use coal fired boilers and hot water to air heat exchangers to avoid product contamination from flue gases. It is understood that many of the conventional hops growers of the USA use hot flue gases in direct contact with the hops. Solar drying technology can also be operated at lower drying temperatures, helping preserve the volatile oil components of the hops (and similarly for other herbs), making for a higher value product. Finally, solar drying is an environmentally favorable sustainable practice.

Other solar hop and herb drying research has been conducted in Spain (Castro Abengoza 2009, Panchon et al 2007 & 2009, Suarez Moya 2009), Serbia(Tesic et al 1993, 1994), Germany (Muller & Martinov 1992, Muller et al 1989,1993), Czech Republic (Mejzr & Hanousek 2007), Yugoslavia (Kisgeci 1988), Tasmania (Doe & Menary 1979) and India (Doe, Bhat, Menary 1979). Little research on this subject since the late 1970s to early 1980s has been located or is known to have been conducted in the United States. Refer to the bibliography at the end of this report for literature citations. Some of the publications are obscure and only retrievable by contacting the original authors, institutions, or via interlibrary loan.

Additional review of the solar hop and herb drying literature is available in the form of a PowerPoint presentation and may be requested from the author of this report. A companion review of determining optimum field hop dry matter for harvest is also available.
Overview of 2011 Solar Hop Drying Research Results –

Readers are referred to the CY 2011 Annual report for this project for details of the first year of the project. It should be posted on the Specialty Crops Program website for Colorado State University.

The 2011 harvest and drying season occurred between 20 August 2011 and September 17, 2011. Seven solar drying tests were conducted during the 2011 campaign. The first three tests used low level hot air captured from the greenhouse attached to the drying barn. Tests 11-4 and 11-5 used hot air captured from the top of the greenhouse. The final two Tests 11-6 and 11-7 used solar heated air collected from an air plenum at the top of the greenhouse. Table 1 summarizes the conditions for these initial tests.

Table 1 - Summary of 2011 Solar Hop Drying Tests

<table>
<thead>
<tr>
<th>Test Number (Dates of Test)</th>
<th>Number of Drying Trays (Hops wt, lbs)</th>
<th>Solar Heat Air Collection System</th>
<th>Weather Conditions</th>
<th>Dryer Inlet Air Temperature, typical range °F</th>
<th>Test duration (hours with fan on)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 0 (System Initial Trial run) (8/20-21/11)</td>
<td>2 trays, 2 stacks</td>
<td>Ambient (outside) air</td>
<td>Good solar radiation, Warm temp</td>
<td>85 to 100 F</td>
<td>25.0 hrs</td>
</tr>
<tr>
<td>No. 11-1 (8/23-24/11)</td>
<td>2 trays, 1 stack, 20 lb hops</td>
<td>Greenhouse air (low level)</td>
<td>Good solar radiation, Warm temp</td>
<td>87 to 99 F</td>
<td>14.8 hrs</td>
</tr>
<tr>
<td>No. 11-2 (8/27-28/11)</td>
<td>2 trays, 1 stack, 20 lb hops</td>
<td>Greenhouse Air (low level)</td>
<td>Good solar radiation, Warm temp</td>
<td>85 to 100 F</td>
<td>11.5 hrs</td>
</tr>
<tr>
<td>No. 11-3 (8/29-31/11)</td>
<td>2 trays, 1 stack, 37 lb hops</td>
<td>Greenhouse air (low level)</td>
<td>Good solar radiation, Warm temp</td>
<td>75 to 95 F</td>
<td>19.6 hrs</td>
</tr>
<tr>
<td>No. 11-4 (8/31/11-9/1/11)</td>
<td>1 tray, 1 stack, 18 lb hops</td>
<td>Top of Greenhouse</td>
<td>Good solar radiation, warm temp</td>
<td>90 to 100 F</td>
<td>10.5 hrs</td>
</tr>
<tr>
<td>No. 11-5 (9/4-5/11)</td>
<td>3 trays, 1 stack, 47 lb hops</td>
<td>Top of greenhouse</td>
<td>Variable solar, cool temp, overcast</td>
<td>80 to 108 F</td>
<td>16 hrs</td>
</tr>
<tr>
<td>No. 11-6 (9/11/11)</td>
<td>1 tray, 1 stack, 17.4 lb hops</td>
<td>Greenhouse roof plenum system</td>
<td>Poor solar, cool temp, cloudy, rain</td>
<td>100 to 120 F</td>
<td>6.2 hrs</td>
</tr>
<tr>
<td>No. 11-7 (9/13-17/11)</td>
<td>2 trays, 1 stack, 32 lb hops</td>
<td>Greenhouse roof plenum system</td>
<td>Poor solar, cool temp, cloudy/humid, variable</td>
<td>65 to 80 F (first 2 days); 75 to 90 F</td>
<td>26.1 hrs</td>
</tr>
</tbody>
</table>

Meteorological conditions during the CY2011 solar hop drying study were variable, as noted on Table 1, particularly for the final two tests when cloudy, cool and rain occurred. Detailed 2011 meteorological data is located in the 2011 progress report, and contained in Appendix A, Figures A-7
through A-16 of this report. Most of the drying tests used hot air temperatures in the range of 90 to 120 °F (32 to 49 °C), generally lower range due to the blower system, pulley/sheave combinations, and motor speeds used. Elapsed drying times were in the range of 6 to 20 hours, except for the adverse weather period which was extended. It should be noted that during the CY2011 tests, the fans were often turned off after daytime hours when temperatures fell and humidity rose. There is some risk with this practice of the incompletely dried hops molding and/or self heating. This practice was altered for the CY 2012 season, leaving the fan on overnight.

Convergence of relative humidity differences between tray inlet to outlet versus hop moisture content was observed. This led to additional focus on this potential control parameter for the 2012 tests to potentially allow determination of optimal drying completion. Figure 2 is a sample chart illustrating for Test 11-6 the observed RH convergence, or delta RH versus the hop moisture drying curve as it approaches the 10% end point. Additional data loggers with digital RH and temperature were acquired for 2012 tests. Air velocity measurements for the hop bed depths used also guided plans for the next season, primarily to avoid lofting of hops, creating blow holes, or unwanted hops agitation and damage as drying completion approached. Certain observed difficulties with the blower/motor system, dryer air leakage, air channeling, air plenum hot air capture also led to design changes for 2012.
Additional 2011 test result data is presented in this report, Appendix C in the form of various graphs for key test numbers 11-4 through 11-7. All data is supported by Excel spreadsheets from automatic data logged temperatures and relative humidity collected at 5 minute intervals, or from thermocouple manual readings.

2012 Solar Hop Drying Research Results

The hops harvest season during CY 2012 came earlier due to the drought and hot weather experienced during 2012. Minimal rainfall for the entire spring and summer occurred. Record temperatures were experienced throughout mid and late summer. The hops matured earlier with harvest beginning August 6 and extending through September 9, 2012.

Hops were picked and processed in the research hop dryer from three farms, Colorado State University Horticulture Research Farm (Fort Collins, Colorado), Niwot Hop Farm (Niwot, Colorado) and J.M. Andrews Farm (Boulder, Colorado). Many of the hops from these farms were sold as fresh hops (or hops nouveau) and not dried. With the remainder there were fourteen individual solar hop drying tests conducted between 20 August and 9 September, numbered as Tests 12-1 through 12-14.

Dryer Equipment and Instrumentation

The solar hop dryer was reconfigured somewhat since the 2011 tests, mostly having to do with some of the input air channeling into the bottom of the dryer, and the position of the blower, moved to inside the barn instead of in the hot greenhouse. Photo #1 illustrates the intake location of greenhouse interior air entry into the plenum space on the side wall of the greenhouse. The hot air collection plenum is 5 to 7 inches thick between the outside greenhouse glazing and the interior mounted shade cloth overlayed by black polyethylene plastic film, both layers fastened to the ribs of the trusses.

Air flows upward through the plenum to the top of the roof arch where it is collected in 10 inch (25 cm) diameter galvanized ducting that penetrates the plastic film. There is a ducting tee with one end fitted with a damper to allow intake of dilution air from near the top of the greenhouse at lower temperature than the air from the plenum space. Under test conditions, this damper was normally closed. A flexible insulated ducting routes the hot air to a blower immediately adjacent to the hop dryer structure. See Photo #2.
The induced draft blower pulls the hot air through the system and pushes it into the dryer air distribution box. See Photo #3 for a view of the blower and the multi-diameter sheaves to allow various air handling rates. The sheaves combinations were varied to produce blower speeds ranging from 1725 to 1740 rpm. A few different electric motors were used at different times during the testing, 1 HP, and nameplate shaft rotation from 2" to 5".

No basic dimensions for the dryer were changed from tests of 2011. Refer to Progress Report for CY 2011 for details, dimensions, and photos of the dryer. The dryer was tightened up some also to reduce some of the leakage and infiltration of cooler air. Minor modifications were made to the hot air plenum system at the top of the greenhouse. Additional photos in Appendix F to this report illustrate some other views of the dryer system and appurtenances. Photo #4 gives an overall view of the dryer. The hop air enters low into a rectangular cross section duct to distribute hot air to 1 or 2 tray stacks.

Photo #2 - Upper right shows greenhouse ducting to remove hot air from plenum and route it to blower and dryer at lower left

Photo #3 - hot air blower and motor into dryer inlet distributor
Photo #4 – Overall view of the dryer. Inlet distributor box on lower right;

Dryer trays in two stacks (shown with 3 left stack trays & one on right).

Photo #5: Dryer tray opened showing the ¼” wire mesh bottom,
covered by a layer of plastic window screening.
Half way through the 2012 tests (for tests 12-7 through 12-14), additional data loggers for temperature and relative humidity (RH) were acquired to obtain more extensive data, notably relative humidity at additional locations. A total of nine data loggers were used in these later tests; Extech brand, EL-USB-2-LCD (www.lascarelectronics.com), with download USB port connector to dump into Excel spreadsheets for analysis. Five had combination temperature and relative humidity logging (3 with digital displays), and four were temperature only without display. Air velocity measurements were made with a portable hot wire anemometer with a telescoping extension wand to insert into air channels (Testo Model 425).

Since most of the data loggers did not have digital displays, numerous thermocouples and a few display RH sensors were placed throughout the system to real time monitor the progress of drying and the operating conditions. An Omega Dataplex ten channel automatic signal scanner was connected to digital temperature readout. Periodic samples of hops were collected from each dryer tray during the drying tests to obtain hops moisture. Moisture was determined by weighing a sample of approximately 10 to 15 grams to nearest 0.1 g before and after drying to bone dry condition in a laboratory oven operating at approximately 100 °C, normally for about one hour. All moisture data in this report are presented as wet basis weight percentages, unless otherwise noted.
Weather Conditions -

Appendix A, Figures A-1 through A-6 present the local meteorological conditions for the entire 2012 test season for ambient air temperature, relative humidity, dew point, solar radiation (cal/m2), clear sky reference radiation, and precipitation. These data are from the nearby Northern Colorado Water Conservancy District weather station number 233 for northwest Boulder (approximately 5 miles west of test site). The beginning and ending times for each solar dryer test are indicated on these graphs. Local ambient temperature and relative humidity were monitored on the actual site with data loggers for most of the tests.

Overall the weather conditions during 2012 hop harvest were favorable for solar drying. There was only minor precipitation at three episodes (see Fig A-6), at the beginning of Test 12-1 (0.02 in; or 0.5 mm), Test 12-7 (~0.04 in; or 1.1 mm), and between Tests 12-12 and 12-13 (0.06 to 0.08 in; or 1.5 to 2.0 mm); very dry. Mean temperatures (Fig A-1) hovered between 70 to 80 F (21 to 27 C) except for a cooling period in the 50 to 70 F (10 to 21 C) range during the final Tests 12-13 and 12-14. Relative humidity ranged between 15% to 70% for most of the season; with peaks >80% during the latter rain events. Daytime solar radiation varied with cloud cover, typically from 60 to 80 cal/m2. The difference between the measured solar radiation and the clear sky reference radiation is a measure of cloudiness.

Operating Variables for Solar Drying Tests -

Table 2 presents a summary of the fourteen solar dryer tests, giving the configurations of the trays and tray stacks, hops depths, general weather condition, dryer operating temperature ranges (inlet), air velocities through the beds, and range of test duration to achieve drying. A key difference among the tests was the configuration of the drying trays. There are two identical stacks of three trays per stack. Depending upon the harvest on any given day, from one to six trays would be used in drying. The test design was mostly dependent upon the progress of the harvest than a well defined and pre-planned test plan, one of the difficulties with on farm research.

This is particularly true during the hectic time of a short term harvest window. The other variable in dryer test configuration was hop depths; again largely determined by the necessity to keep the various hops from individual farms separated for harvest accounting and independent marketing purposes. In the case of the Colorado State University hops, their hops were part of a hop irrigation and yield study. The CSU hops included numerous hop varieties and each replicate of an irrigation regime/hop variety test needed to be separately weighed and processed, again affecting the way each batch was loaded into the solar dryer.
<table>
<thead>
<tr>
<th>Test Number (Dates)</th>
<th>Number of Drying Trays</th>
<th>Tray and Stack Configuration</th>
<th>Weather Condition</th>
<th>Hops depth, inches</th>
<th>Dryer Inlet Temp F</th>
<th>Air Velocity thru bed m/s</th>
<th>Test Duration w/fan on hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-1 (8/20-21/12)</td>
<td>3</td>
<td>single</td>
<td>Clear, Sunny, warm</td>
<td>Limited data</td>
<td>105 to 113 F</td>
<td>0.02 to 0.03</td>
<td>~7 hr (no fan Overnight, day only)</td>
</tr>
<tr>
<td>12-2 (8/22-23/12)</td>
<td>2</td>
<td>single</td>
<td>Variable, Sun-cloud, Lt. rain</td>
<td>1.5 to 2&quot; top; 3.5 to 4&quot; btm</td>
<td>75 to 137 F</td>
<td>0.02 to 0.03</td>
<td>17.5 hr (fan on overnight and daytime)</td>
</tr>
<tr>
<td>12-3 (8/24-25/12)</td>
<td>1</td>
<td>single</td>
<td>Warm, 30-40%RH</td>
<td>3 to 3.5&quot;</td>
<td>70 to 130 F</td>
<td>0.02 to 0.03</td>
<td>21 hr (overnight)</td>
</tr>
<tr>
<td>12-4 (8/25-26/12)</td>
<td>2</td>
<td>single</td>
<td>Clear, warm</td>
<td>2 to 2.5&quot;</td>
<td>70 to 134 F</td>
<td>0.02 to 0.03</td>
<td>14.5 hr</td>
</tr>
<tr>
<td>12-5 (8/28/12)</td>
<td>4</td>
<td>Double; 2/stack</td>
<td>Variable, Sunny-cloudy</td>
<td>2 to 4.5&quot; Varied by tray</td>
<td>88 to 117 F</td>
<td>0.02 to 0.03</td>
<td>6 hr</td>
</tr>
<tr>
<td>12-6 (8/30/12)</td>
<td>3</td>
<td>Double 1 left; 2 right</td>
<td>Variable; sunny</td>
<td>2.5 to 4&quot; Varied by tray</td>
<td>92 to 138 F</td>
<td>0.02-0.03</td>
<td>7 hr Day only</td>
</tr>
<tr>
<td>12-7 8/31-9/1/12</td>
<td>6</td>
<td>Double 3 left; 3 right</td>
<td>Variable; Rain at end test</td>
<td>3 to 5&quot;</td>
<td>70 to 124 F</td>
<td>0.02 -0.03</td>
<td>13.5 hr Overnight; Fan problems</td>
</tr>
<tr>
<td>12-8 9/1-2/12</td>
<td>6</td>
<td>Double 3 left; 3 right</td>
<td>Variable; It rain at end</td>
<td>3 to 5&quot;</td>
<td>75 to 149 F</td>
<td>0.05 to 0.06 velo tests</td>
<td>15 hr overnight</td>
</tr>
<tr>
<td>12-9 9/2-3/12</td>
<td>2</td>
<td>Double 1/stack</td>
<td>Cloudy start</td>
<td>3 to 4&quot; See partial data log</td>
<td>See partial data log</td>
<td>0.05 to 0.06</td>
<td>19 hr overnight</td>
</tr>
<tr>
<td>12-10 9/3-4/12</td>
<td>2</td>
<td>Double 1/stack</td>
<td>Warm, dry,</td>
<td>4.5 to 5&quot;</td>
<td>80 to 127 F</td>
<td>0.08 to 0.14 velo tests</td>
<td>17.5 hr overnight</td>
</tr>
<tr>
<td>12-11 9/4-5/12</td>
<td>3</td>
<td>Double 1 left; 2 right</td>
<td>Cooler, dry</td>
<td>Not recorded</td>
<td>to 126 F</td>
<td>0.08 to 0.14</td>
<td>15 hr Overnight</td>
</tr>
<tr>
<td>12-12 9/5-6/12</td>
<td>2</td>
<td>Double 1/stack</td>
<td>Cloudy, humid at end</td>
<td>2.5 to 4.5&quot;</td>
<td>70 to 136 F</td>
<td>(a)0.08 to 0.12 (b) 0.23 Velos tests</td>
<td>15 hr Overnight</td>
</tr>
<tr>
<td>12-13 9/7-8/12</td>
<td>3</td>
<td>Double 1 left; 2 right</td>
<td>Cloudy, cooler</td>
<td>3 to 4&quot;</td>
<td>54 to 122 F</td>
<td>0.10 to 0.11</td>
<td>17 hr Overnight</td>
</tr>
<tr>
<td>12-14 9/8-9/12</td>
<td>3</td>
<td>Double 2 left; 1 right</td>
<td>Partly cloudy, cooler</td>
<td>2.5 to 5.5&quot;</td>
<td>52 to 135 F</td>
<td>0.11 to 0.14 Velos tests</td>
<td>18 hr overnight</td>
</tr>
</tbody>
</table>
Hop drying rate is affected by several dryer operating variables. Hop depths in each tray were measured at the beginning of each test. That data is summarized in Table 3a. Hop depths in 2011 and 2012 series were all relatively shallow compared to conventional drying depths of 36 to 40 inches (0.9 to 1 m). They ranged from 2.0 inches to 5.5 inches (5.1 to 14 cm). Hops depth for the 2011 Tests are presented in Table 3b.

### Table 3a - Hop Depths (inches by dryer tray location) in Drying Trays, 2012 Tests

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Bottom Left</th>
<th>Middle Left</th>
<th>Top Left</th>
<th>Bottom Right</th>
<th>Middle Right</th>
<th>Top Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-1</td>
<td></td>
<td></td>
<td></td>
<td>3.0 to 3.5</td>
<td>3.0 to 3.5</td>
<td>3.0 to 3.5</td>
</tr>
<tr>
<td>12-2</td>
<td></td>
<td></td>
<td></td>
<td>3.5 to 4.0</td>
<td>1.5 to 2.0</td>
<td></td>
</tr>
<tr>
<td>12-3</td>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>12-4</td>
<td></td>
<td></td>
<td></td>
<td>2.0 to 2.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>12-5</td>
<td>4.0 to 4.5</td>
<td>2.0 to 3.5</td>
<td></td>
<td>3.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>12-6</td>
<td>2.5 to 3.0</td>
<td>3.0</td>
<td>2.5</td>
<td>3.5 to 4.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>12-7</td>
<td>2.5 to 3.0</td>
<td>3.0</td>
<td>2.5</td>
<td>4.5 to 5.0</td>
<td>4.5</td>
<td>4.0 to 4.5</td>
</tr>
<tr>
<td>12-8</td>
<td>5.0</td>
<td>2.5 to 3.0</td>
<td>2.5</td>
<td>4.5 to 5.0</td>
<td>4.5</td>
<td>4.0 to 4.5</td>
</tr>
<tr>
<td>12-9</td>
<td>3.5 to 4.0</td>
<td></td>
<td></td>
<td>3.0 to 3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-10</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>12-11</td>
<td>Not available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-12</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td>4.0 to 4.5</td>
<td></td>
</tr>
<tr>
<td>12-13</td>
<td>3.5 to 4.0</td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
<td>3.0</td>
</tr>
<tr>
<td>12-14</td>
<td>3.5</td>
<td>2.5</td>
<td></td>
<td></td>
<td>5.5</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3b - Hop Depths (inches by dryer try location) in Drying Trays, 2011 Tests

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Bottom Left</th>
<th>Middle Left</th>
<th>Top Left</th>
<th>Bottom Right</th>
<th>Middle Right</th>
<th>Top Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-1</td>
<td>Not available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-2</td>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td>11-3</td>
<td></td>
<td></td>
<td></td>
<td>5.25</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>11-4</td>
<td></td>
<td></td>
<td></td>
<td>4.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-5</td>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>11-6</td>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-7</td>
<td></td>
<td></td>
<td></td>
<td>3.2</td>
<td>3.2</td>
<td></td>
</tr>
</tbody>
</table>

Note: blank cells in the tables indicate that these trays were not in use for the noted test, or in a few tests that the hop depths were not measured (tests 11-1 and 11-11). To convert to centimeters multiply inches by 2.54

Air velocity was measured at several times during selected tests, usually associated with a change made to the blower system to adjust fan speed (rpm) by changed pulley/sheave combinations or to replace motor drives. Air velocity data is summarized in Table 4a for selected 2012 tests and in Table 4b for selected 2011 tests. Notations for interpretations and associated comments are provided below each table. For each tray the air velocity was measure at five different locations, approximately 1” to 1.5” (2.5 to 3.8 cm) above the surface of the hops. The sample locations were center, and at approximate center of each quadrant of the bed. For the horizontal rectangular dryer inlet duct six locations of the cross section of the duct were measured, approximately 2 feet (0.6 m) before the split of the air stream into the two tray stacks. Locations were at center near top of duct, at center near bottom of duct, and four on the horizontal center line of the duct. Hot wire telescopig probe was
slipped into a narrow slot to avoid disturbing the air flow streams. For each location five measurements were made for approximately 20 seconds each. The anemometer electronics averaged rapid measurements for each sample period and provided a digital display of air velocity means in meters per sec (m/sec) as well as air temperature. Data for means of five measurements were calculated and are recorded in the tables below.

Table 4a - Drying Bed Air Velocity for 2012 Solar Hop Drying Tests

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Air Velocity Into Dryer m/sec</th>
<th>Air Volume Into Dryer m³/sec</th>
<th>Left Stack Air Velocity Exiting Bed m/sec</th>
<th>Right Stack Air Velocity Exiting Bed m/sec</th>
<th>Blower Speed (calc'd) rpm</th>
<th>Motor Speed (nameplate) rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-1 to 12-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-5*</td>
<td>0.76</td>
<td>0.36</td>
<td>0.03</td>
<td>0.025</td>
<td>1078</td>
<td>1725</td>
</tr>
<tr>
<td>12-6</td>
<td>0.83</td>
<td>0.39</td>
<td>0.03</td>
<td>0.025</td>
<td>1078</td>
<td>1725</td>
</tr>
<tr>
<td>12-7</td>
<td>0.89</td>
<td>0.42</td>
<td>0.06</td>
<td>0.060</td>
<td>1479</td>
<td>1725</td>
</tr>
<tr>
<td>12-8*</td>
<td>0.89</td>
<td>0.42</td>
<td>0.08</td>
<td>0.144</td>
<td>1479</td>
<td>1725</td>
</tr>
<tr>
<td>12-10*</td>
<td>0.83</td>
<td>0.39</td>
<td>0.08</td>
<td>0.144</td>
<td>1479</td>
<td>1725</td>
</tr>
<tr>
<td>12-11</td>
<td>0.72</td>
<td>0.34</td>
<td>0.12</td>
<td>0.08</td>
<td>1479</td>
<td>1725</td>
</tr>
<tr>
<td>12-12a*</td>
<td>0.85</td>
<td>0.40</td>
<td>0.12</td>
<td>0.08</td>
<td>1479</td>
<td>1725</td>
</tr>
<tr>
<td>12-13*</td>
<td>0.91</td>
<td>0.43</td>
<td>0.10</td>
<td>0.11</td>
<td>1479</td>
<td>1725</td>
</tr>
<tr>
<td>12-14*</td>
<td>0.93</td>
<td>0.44</td>
<td>0.11</td>
<td>0.14</td>
<td>1479</td>
<td>1725</td>
</tr>
</tbody>
</table>

Notes: Air velocities measured for tests marked with *. For other tests velocities assumed same as preceding test since blower and motor or other configurations were not changed. Sheave combinations changed between 12-7 and 12-8, and blower relocated. Blower rpm calculated from pulley sheave ratio combinations.

Table 4b - Drying Bed Air Velocity for 2011 Solar Hop Drying Tests

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Air Velocity Into Dryer m/sec</th>
<th>Air Volume Into Dryer m³/sec</th>
<th>Left Stack Air Velocity Exiting Bed m/sec</th>
<th>Right Stack Air Velocity Exiting Bed m/sec</th>
<th>Blower Speed (calc'd) rpm</th>
<th>Motor Speed (nameplate) rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-5a*</td>
<td>1.48</td>
<td>0.702</td>
<td>0.25</td>
<td>n/a</td>
<td>1088</td>
<td>1740</td>
</tr>
<tr>
<td>11-5b*</td>
<td>1.82</td>
<td>0.863</td>
<td>0.063</td>
<td>0.10</td>
<td>1088</td>
<td>1740</td>
</tr>
<tr>
<td>11-5c*</td>
<td>2.07</td>
<td>0.981</td>
<td>0.10</td>
<td>0.05</td>
<td>870</td>
<td>1740</td>
</tr>
<tr>
<td>11-6a*</td>
<td>0.84</td>
<td>0.398</td>
<td>0.18</td>
<td>0.06</td>
<td>2784</td>
<td>1740</td>
</tr>
<tr>
<td>11-6b*</td>
<td>1.26</td>
<td>1.36</td>
<td>0.18</td>
<td>n/a</td>
<td>870</td>
<td>1740</td>
</tr>
<tr>
<td>11-6c</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>2784</td>
<td>1740</td>
</tr>
<tr>
<td>11-6d</td>
<td>0.84</td>
<td>0.398</td>
<td>0.06</td>
<td>0.06</td>
<td>870</td>
<td>1740</td>
</tr>
<tr>
<td>11-7a</td>
<td>0.84</td>
<td>0.398</td>
<td>0.06</td>
<td>0.06</td>
<td>870</td>
<td>1725</td>
</tr>
<tr>
<td>11-7b</td>
<td>0.45</td>
<td>0.213</td>
<td>0.02</td>
<td>0.02</td>
<td>1592</td>
<td>1725</td>
</tr>
<tr>
<td>11-7c*</td>
<td>1.15</td>
<td>0.545</td>
<td>0.08</td>
<td>0.02</td>
<td>2760</td>
<td>1725</td>
</tr>
<tr>
<td>11-7d*</td>
<td>0.45</td>
<td>0.213</td>
<td>0.02</td>
<td>0.02</td>
<td>1592</td>
<td>1725</td>
</tr>
<tr>
<td>11-7e</td>
<td>0.45</td>
<td>0.213</td>
<td>0.02</td>
<td>0.02</td>
<td>1725</td>
<td>1725</td>
</tr>
</tbody>
</table>

Notes: Left stack of trays not used during these 2011 tests. Air velocities measured for tests marked with *. For other tests velocities assumed same as preceding test since blower and motor or other configurations were not changed. Pulley/sheave combinations (and resulting blower rpm) changed numerous times during some of these tests. Blower rpm calculated from pulley sheave ratio combinations.
The above velocities can be converted into cubic feet per minute (cfm) (or m³/min), and often for facility designs are expressed as air flow cross sectional loading or cfm/ft² of bed area.

Maximum recommended air velocities are based on avoidance of bed fluidization or development of blow holes during the drying process to prevent bypass of the drying air and uneven drying across the bed. Bed agitation is also to be avoided, particularly at the end of the drying process to prevent loss of lupulin from the hop flowers.

Maximum recommended velocities are a function of bed depth and the moisture content of the hops, the latter factor varying from dense moist hops (typically 65 to 100 kg/m³) at the beginning of drying to much lighter density hops at the end of the drying (typically 30 to 40 kg/m³). Various researchers have investigated these criteria but usually for much deeper hop depths, from 12 to 40 inches (0.3 to 1.0 m) than used in this series of tests. Tesic et al (1994) evaluated drying times versus hop depth ranging from 0.25 to 1.15 m and air velocities ranging from 0.12 to 0.22 m/s in a solar hot air dryer. See Figure 5 below. Extended drying times of 102 and 130 hours were required at 0.85 m and 1.15 m hop depths. Air velocity through hop beds ranged from 0.12 to 0.22 m/s. Lowest drying time of 17 hours was required for 0.25 m (10 inches) bed depth and air velocity of 0.22 m/s with an average drying air temperature of 29 °C.

Other researchers have suggested reasonable air velocities through drying beds of 0.1 to 1.0 m/sec, for bed depths of 12 to 20 inches. See Fig. 5 below for the data from Zeisig (1970) and Bailey (1958) illustrating the observed effects on drying time at various air temperatures and air velocities. The Zeisig data are for hop bed depth of 30 cm (12 in); hop depth for Bailey data is not known. It should be noted that most of the drying temperatures with Zeisig and Bailey research were elevated (50 to 80 °C)(122 to 176 °F) and using conventionally fueled hop dryers, not the lower temperature solar drying ranges (32 to 52 °C)(90 to 125 °F). Consequently solar drying times using the lower air temperatures are typically longer. Additional analysis of solar drying duration is provided later in this report.
Appendix E of this report presents supplemental summary information from these authors for reference.

![Graph of Hop Drying Times vs Air Velocity and Temperature]

For the current tests (2011-2012) of this GREG study the cross sectional area of each dryer tray was 14.0 ft² (1.30 m²). The dryer input air volume rates tested ranged from approximately 0.2 to 0.5 m³/sec/tray stack (7 to 17.5 cfm/tray stack). Since commercial blowers are often specified based upon the air volume rates, this is a more useful means to select appropriate blower capacity and associated motors.

In a few tests during the 2012 series at higher air velocities, a limited amount of bed lofting and blow hole or nesting development occurred. From these experiences, velocities in shallow hop layers of less than 6 inches (15 cm) should remain less than approximately 0.1 m/s (0.3 ft/sec). A detailed engineering study of optimal air velocity through hops beds was not part of this study. That additional analysis may be conducted by the principle investigator and be made available in other publications.

**Individual Dryer Tests Results for 2012 and 2011**

The operational system monitoring data for each season 2012 solar dryer test is presented in Appendix B (for 2012) and Appendix C (for 2011). Data is presented in graphical form as the following charts for most tests:

- **Solar Dryer System Temperatures** for all major locations in the dryer, plus solar radiation (a dotted line with magnitudes read from the right side ordinate scale). One should take note of the high temperature location, Top Greenhouse Plenum, and the Dryer Inlet. The exit temperature for each tray is also notable to see the temperature drop across the tray due to the evaporative cooling effect during hop drying. As the hops approach final moisture the
differences in temperature across the bed tend to converge since no additional evaporative loss is occurring. It is also of note to see the temporal offset of the peak in solar radiation and the peaks of the system temperatures, a lag time that occurs.

- **Solar Dryer System Relative Humidities** for key locations within the dryer are presented, as well as the hops moisture drying curve superimposed. This is done to illustrate the relationship between the convergence of the RH between inlet and exit for each tray. For many of the tests, as the difference between these two RH measures nears zero or a small value, the hops have also neared the optimum 10% moisture value. This seems to be only approximately valid near the end of the drying however, and in some instances crossover can occur which may relate to the configuration of the dryer stacks and which tray position one is examining, i.e. bottom, middle, or top position. For dryer configurations in which more than one stack was used and multiple trays in each stack, separate graphs are provided for each tray and stack.

- **Left or Right Stack Drying Conditions (number of trays)** graphs are provided for some of the tests, particularly those with multiple trays in each stack. These graphs illustrate the progression of temperatures and relative humidity values as drying air progresses through the system. On some of these graphs the hops drying curves have also been superimposed.

- **Drying Curves and Drying Rate Curves** are also included in the appendices for many of the tests. Conventional hop drying curves are plotted as hop moisture vs. elapsed drying time. Drying rate curves plot hop moisture (x axis) vs. the rate of change of hop moisture per unit time. The rate curves are particularly useful to illustrate the differing drying rates during day and night conditions, and for different stages of hop flower dry down.

If some significant change in operating conditions such as a change in the blower speed or moving or removing trays from one position to another, that information will be noted on the graphs. As drying progresses, the bottom trays typically will dry more quickly than upper (middle and top position) trays. To avoid over-drying, the trays that have reached the optimum 10% moisture are removed and upper trays are moved downward. This requires a temporary shut-down of the hot air blower, so one can observe peaks or valleys of the traces for temperature and RH.

On some graphs dew point temperature is shown. This generally has no particular significance at the operating conditions of the solar dryer. It could have meaning in poor weather conditions, or during overnight times, and might indicate when the hops might have a tendency to absorb moisture rather continue drying. Many of the tests during 2012 were started in the late afternoon or evening, meaning that inlet temperatures were much lower than daytime and relative humidity was generally higher. One can observe that some of the drying curves are not as steep during these conditions, as would be expected.
Analysis and Interpretations of 2011 and 2012 Solar Drying Data —

To make use of the data collected for dryer operations and dryer design parameters, various correlative analyses of test data have been conducted. One such analysis was to plot the drying curves, hops moisture versus elapsed time, in an attempt to potentially determine the rate of drying from the slope of the curves. The drying curves for each test are presented in Appendix D.

Due to the highly variable temperature and relative humidity inlet conditions that occur with this solar drying system due to changing weather conditions during the day, and certainly due to the diurnal solar radiation cycle, the interpretation is much more complex than a dryer that is heated by a controllable energy source and operated for a constant dryer air temperature and relative humidity. In general, even with a constant temperature dryer, there are several phases in drying of a plant material such hops. This is illustrated by two theoretical or generic hop drying curves in Figure 7 and 8 below (Loewer, Bridges, & Bucklin, 1994) (Bennett & Myers 1962).

![Fig. 7 - Generic Hops Drying Curve (both wet and dry basis shown)](image-url)
The initial drying stage is heating of the hops, which is then followed by removal of free water at the surface of the hop bracteoles. As the surface of the hop bracts gets drier, some transport of moisture from the internal tissue occurs by diffusion or capillary action; this stage typically being the fastest drying rate (under constant temperature and relative humidity conditions). In the final stages, the bracts are quite dry and the center of the strobile, strig, or stem of the hop flower can still retain significant moisture. This stage drying rate is often somewhat slower. Over drying to remove all of the moisture for the stem or strig may cause the hop flower to become brittle and the bracts to fall off or shatter, exposing the valuable lupulin glands. One does not want this to happen, leaving all that golden material on the barn floor during handling, baling or packaging; so drying to bone dry condition is not desired. It has been determined over the decades and centuries that drying to approximately 10% by weight, wet basis, will result in a final equilibration to desired moisture within the hop flower for a storable product condition. Figure 9 illustrates the equilibrium moisture content of hops at various storage relative humidity values (Henderson 1973).
From the above equilibrium moisture content curve, one can deduce relevant guidance for storage conditions for dried hops. In regions such as the arid west with low relative humidity, often in the range of 20 to 30%, the equilibrium hop moisture will tend toward 4 to 6% moisture, lower than desirable. To prevent this lowering of optimal moisture during storage, compressing the hops into bales or storing in refrigeration and controlled humidity environments near the equilibrium 50 to 60% RH is recommended. Other relevant points are that one does not wish to deliver over-dried hops: (1) brewers and brokers expect optimum conditions according to established industry standards; (2) shattered cones with bracts falling off can result in loss of the lupulin; and (2) since hops are sold by weight in most cases, loss in delivered weight means loss of profits to the grower.

From the dryer data of the current research tests, the mean drying rates for night-time and daytime periods and observed stages of drying have been calculated. Those rates for the various tests are presented in Appendix D for the 2012 and 2011 test years. The test data for nighttime moisture content trends is limited so the slopes of the drying curves during those periods are also limited.

A few hop drying rate graphs and conventional hop drying curves of the solar drying tests during 2011 and 2012 are presented below.

Figure 10a shows drying rate curves for Test 12-8, a test with 6 drying trays in use in two separate stacks of three trays each, identified as the right and left stacks, and bottom, middle and top positions in the stack. This test was conducted with low air velocity through the beds, 0.045 to 0.070 m/sec. The left stack of trays had slightly lower air velocity and air flow through the trays (0.045 to 0.054 m/sec) than the right stack of trays (0.06 to 0.07 m/sec). The dryer inlet temperature ranged from the mid to upper 60s F during the night time hours and rose to 128 F by mid day, then declining somewhat for the final hour of the drying. The dryer inlet relative humidity ranged in the upper 60% during the night, dropped to about 40% by 9:00 and dropped to 9 to 11% by mid-day. Solar radiation was good in the early morning, peaking about 10:00 at 60 cal/m², then becoming cloudy through mid day, falling to 20 to 30 cal/m² at mid-day then down to 11 cal/m² at the end of the dryer test. The various shapes of the drying rate curves relate to the different starting moisture content of the hops, and the time of day in drying. This test began very late at night at the end of a picking campaign, the dryer fan on at 22:10 hours. It ran until 14:43 hours the next day.

The progress of drying with each curve goes from the start at the right and moves to the left as the hop moisture declines. The top left tray and the bottom right trays had low starting moisture content hops, 20% and 41%, respectively, hence the low drying rates for these trays. The bottom right tray was removed at 13:15 and the top right tray moved into the bottom right position to finish drying. The most distinctive drying rate curve is the middle left position tray which illustrates the upward climb in drying rate as the hop bracts dry (right side of the curve), then the steep decline in drying rate at the finish (left side of the curve). The top right position tray shows a similar profile. The middle right tray illustrates slow and nearly constant drying in the beginning followed by a steep rise to a plateau, then a decline at the end. The rate curves for each tray are shown on the graph.
Figure 11a shows the drying rate curve for Test 12-14, a test with three drying trays (solid lines) during less favorable solar conditions, higher ambient relative humidity, lower solar radiation, and lower ambient temperatures. The progress of drying is from right to left on these graphs (x-axis traces the drop in hop moisture). The hops were loaded into the dryer and the fan started at 16:50 hours (late afternoon); removed upon drying completion the following day at 13:30 hours. The drying rate during night time period is relatively low and nearly constant at about 0.025 lb water removed/lb dry hops-hour. With sunrise the dryer inlet air heats up (dot-dash light blue line) and RH drops (dash purple line), the drying rate rapidly increases until the hops reach the final drying stage and the drying rate falls again as the center stem dries. This test had a longer duration drying period than Test 12-8 (Figure 10).

Weather conditions during Test 12-14 were variable but generally good solar radiation with minimal clouds. Ambient air temperatures were lower than most of the other 2012 season drying tests, averaging about 60 to 65°F, starting at about 75°F at the start of the test and ending at about 85°F on the next day at completion of the drying; nighttime lows were near 50°F. Ambient relative humidity averaged about 45% for the test, mid 20s % at mid-day to 60% during the night.

Air flow and velocity through the hop drying beds for Test 12-14 was higher than Test 12-8. The velocity though the left stack of trays ranged from 0.09 to 0.13 m/sec, and for the right stack was about 0.14 m/sec.

**Figure 11a - Hops Drying Rate Curve (dry basis)**
*Test 12-14, Sept 8-9, 2012*
Superimposed on Figure 11a are curves that approximately correspond to the trends for dryer inlet average temperature and relative humidity to assist in interpreting the shapes of the drying rate curves. Three trays were in use for this test, one on the right stack and two in the left stack. The two bottom position trays have nearly identical drying rate profiles. The middle left position tray has an offset to the right in its drying rate profile. The day and night time periods are approximately indicated. Starting from the right of the graph, the hop drying progresses to the left. The Test 12-14 drying test began in late afternoon, 16:50 hours. Inlet dryer temperature began at approximately 100°F, with relative humidity at less than 20%. During the night the dryer inlet temperature fell to a stable 60°F and a gradually rising relative humidity between 40 and 60%. During this night time period the hops drying rate was constant in all drying trays, ranging around 0.025 lb water removed per pound of dry hops per hour. After sunrise, dryer inlet temperatures rose to over 130°F at the end of drying, and RH fell to 10%. The hop drying rate rose during this period to a peak of 0.06 to 0.07 for the bottom position trays, and to 0.05 lb water removed/lb dry hops/hour for the middle position tray. Upon reaching virtually complete drying of the bracts the rate fell sharply to the end of the test when the hops reached the 10% w.b. completion target. For comparison the standard hop drying curve for Test 12-14 is presented below for Test 12-14 (Figure 11b). This type of curve is typically used to track the progress of the drying during actual runs since it is easier to utilize to determine the end point, and when to terminate the fans and remove the dried hops from the trays.
Predictive Correlations for Determining Drying Completion and Potential Automation

During the 2011 tests it was observed that as the inlet and outlet relative humidity of each drying tray converged near the end of a drying cycle, that condition may be correlated to the achievement of the desired 10% optimal hop moisture content. See Figure 2 earlier in this report which overlaid the progress and convergence of inlet and outlet relative humidity for a tray during a 2011 test versus the hop moisture decline curve.

Two tests of this hypothesis were conducted with the data from the 2012 series of solar drying tests, one comparing exit relative humidity to hop moisture content for a drying tray, the other comparing the difference between inlet and exit relative humidity of a drying tray. Figure 13 for Test 12-14 below is an example of the trends observed of hop moisture plotted versus tray exit relative humidity. This observed trend provided encouragement that relative humidity trends, an easily measured parameter could be used for determining or predicting the end point for a hop drying run. Figure 14 is the companion graph for the same Test 12-14 using the difference in relative humidity between drying tray inlet and exit versus hop moisture content. It too was generally encouraging.

Fig 13: Tray Exit Relative Humidity vs. Hop Moisture % Solar Hop Drying Test 12-14, Sept 8-9, 2012

- Btm Right Tray 14 cm (5.5 in)
- Btm Left Tray 8.9 cm (3.5 in)
- Middle Left Tray 6.4 cm (2.5 in)

Notes:
1. Relative humidity is measured at the exit from each tray.
2. The hop depths are indicated for each tray in the legend.
In Figure D-1 through D-4 (Appendix D) are graphs of the RH versus moisture in a scatter plots using data for all trays, all tests, and for the entire duration of test periods. Those scatter plots were truly scattered and produced a poor correlation coefficient R values ranging from 0.25 to 0.57, meaning that they are not a reliable predictor tools. It is suggested that instead of examining the entire set of RH values for any given drying run to check for convergence of inlet and outlet values, that only the final few hours of a run may be more indicative of the approach to drying completion as the relative humidity convergence of tray inlet and outlet occurs. This secondary hypothesis is yet to be tested. There is limited published literature that indicates others have successfully used this technique to automate hop dryers (Friedrich and Horder 2009). More work is needed in this area.

More Interpretation of Data Recommended -

Given the large amount of data collected during both 2011 and 2012, the above described analysis can be further enhanced with this data base to seek drying time correlations using the change in hop moisture versus equilibrium moisture, and system operating parameters such as air velocity, bed depth, bed air temperature and relative humidity. The drying air velocity and hop bed depth data can also be further analyzed within the ranges studied to determine the effects of these variables on drying rates. The original scope of the project did not anticipate a full engineering analysis. Additional analysis is also warranted to further examine the potential to use system temperature and relative humidity measurements to signal completion of the drying process, ultimately for automating the shutdown or
variation of other operating factors of the dryer such as temperature control with dilution air
dampering, recirculation of dryer exhaust air or varying air velocity at different stages of the drying.
That additional work will continue by the investigators, and perhaps others. Some of the mathematical
equations developed by earlier investigators into both conventional fuel and solar drying are planned to
be studied from this data base, including specifically the work of Zeisig (1957), Thompson, Stone and
others. Appendix E contains some supplemental materials with hop drying rate models and
correlations that may be able to be tested with data from the current tests. Other analysis that may be
possible from this data set could include psychometric or thermodynamic energy and exergy evaluations
to evaluate potential improvements in the solar collector system parameters and designs, and to
provide a means to evaluate other sites with different solar conditions for applicability of solar hop
drying in other locations.

Conclusions and Recommendations –

Solar hot air drying of hops was found to be effective with the system used in this study, and for
the local site conditions during two seasons of testing. These methods and equipment can be
replicated by other hop and herb growers and processors with similar solar site conditions in Colorado
and elsewhere. The entire system is relatively inexpensive, and could make use of greenhouse space
that is commonly not engaged during hot summer season of the hop harvest season. The system built
for these tests was largely assembled from salvage materials, including fans, motors, pallet racking, with
limited new materials and construction labor.

Improvements in the system are clearly possible to dry the hops more quickly by building a
more air tight dryer to more efficiently transfer the hot air from the greenhouse roof plenum to the
drying beds. Computer controlled or programmable logic circuit systems based on real time system
temperature and relative humidity data are considered very possible to automate the process and
remove necessity for some of the operator attention to avoid over drying or under drying.

Use of this system can clearly be transferrable to drying other agricultural products, notably a
wide variety of herbs which also should be dried at relatively low temperatures and without concern of
contamination for fuels and flue gases. One brief trial was successfully conducted with solar drying of
English comfrey leaf but not documented with detailed data collection.

Further work is warranted to evaluate the benefits and performance of solar hot water storage
systems to allow continued higher temperature drying after the sun goes down. Improving the speed
of drying can dramatically increase the drying throughput capacity, making better use of limited
equipment resources and drying bed area. That element of this study was not conducted due to
limitations in the available funding. Such solar energy hot water or other heated media storage systems
will necessarily be more expensive and more mechanically complex than the simple hot air greenhouse
plenum system. However such solar hot water systems are well proven in other applications and are
easily adapted to provide heat via a hot water radiator system to heat the dryer air. They should prove very effective and further investigation and demonstration is recommended.

Additional solar drying investigations with hop quality measurements of alpha and beta acids, plus other individual volatile oil chemicals, at lower dryer operating temperatures are also recommended.

Respectfully submitted by:

Richard D. Andrews, General Partner

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