Introduction

Greenhouse hydroponic vegetable production has been highly developed in northern climates over the last 100 years. In the last decade production of especially tomatoes has been established in the desert southwest of the United States primarily due to the high solar radiation which allows for year around production. Automated environmental computer control systems have sufficiently matured to provide optimum conditions for plant growth. Drip irrigation and bag culture have become the norms supporting high-wire culture of plants for up to one year. Root zone aggregates, including Rockwool, perlite, peat/vermiculite, coconut coir, volcanic rock and urethane foam, have all proven capable of supporting a healthy plant with yields of 50 kg m$^{-2}$ or more. This paper presents cultural practices for tomato production on Rockwool using drip irrigation techniques.

The Water Source (see Schematic 1, Materials #1)

Any hydroponic nutrient solution begins with the “source water”. The source water can be obtained from a city water supply, a private well or through water harvesting (channeling rain water into catchments).

There must be a sufficient quantity of water available for plants and for cooling. For mature tomatoes, in greenhouse hydroponics, allow 4 liters/plant/day. If evaporative cooling is used, especially in desert areas, the water needs for greenhouse cooling may double that number.

The source water must also be of the appropriate quality. The water must be adjustable to a final feed pH (measure of acidity/basic properties) of 5.5 to 6.5 for tomatoes (and most plants). The salt content, measured as EC (electrical conductivity), TDS (total dissolved solids), ppm (parts per million) etc., should also be relatively low. Certain geographic areas have high salt levels in the water. High boron, fluoride, chloride, sulfates and sodium can cause poor plant growth. High lead, cadmium, aluminum, silver and other heavy metals can be toxic to plants or can be absorbed by plants in limited or large amounts (ex: vegetables grown in Colorado mining areas contain excess lead and cadmium). High iron levels, especially in “hard water” (high in calcium and magnesium) can cause rusty spots on leaves when overhead irrigation is used. Finally, high overall salt levels can cause rapid salt buildup on cooling pads. The cooling water may need to be bled off and replaced with fresh water on a regular basis.

If the source water contains large amounts of elements normally used by the plants, the nutrient recipe may have to be adjusted to take into account nutrients already in the water.

Injectors With Nutrient Reservoirs (see Schematic 1, Materials #2)

For small hydroponic systems, full strength nutrient solution can be mixed and added directly to the plant root zone. However, for larger systems, with automated drip irrigation, the
nutrient solution needs to be made in concentrated form in stock tanks. Usually 3 tanks are employed (1-acid, 2-calcium/nitrates/iron, 3-all other macros/micros) in order to keep compounds containing calcium separated from those containing phosphates or sulfates. If these are combined in high concentration, they will form a precipitate, sink to the bottom of the tank and become unavailable to the plants causing nutrient deficiencies. Macro nutrients are those elements needed in large amounts by plants (nitrogen, phosphorous, potassium, calcium, sulfur and magnesium), whereas the micronutrients are those elements needed in small amounts (boron, copper, iron, zinc, chloride, molybdenum and manganese).

Premixed liquid or powder concentrates can be purchased. However, most commercial growers choose to mix their own nutrient solutions themselves. Many specific recipes are available and differ depending on the crop being grown. For example, most leafy crops grow better with more nitrogen (300 ppm), whereas fruiting crops such as tomatoes will do better with lower (200 ppm) nitrogen levels. The recipe can also be changed depending on the plant’s stage of development. For example, as the tomato plants begin to produce and set flowers/fruit they will require higher levels of potassium (starting at 280 ppm for the seedling and early vegetative phase and raising to 350 ppm during the flowering and fruiting of the mature phase). If the appropriate technology is available, it is also helpful to be able to vary the electrical conductivity (EC) during the day or during times of cloudy verses sunny weather. During times of low light (cloudy, early or late in the day) a higher EC can be employed, whereas, during times of high light (mid-day, sunny) the plants need more water, especially for transpirational cooling such that a lower EC (more dilute solution) can be used.

Injectors of various types are available that can either be manually set or combined with an irrigation controller/timer to allow for the appropriate dilution of the concentrated nutrient solution.

**PVC Pipe, Connectors, Elbows, Etc. (see Schematic 1, Materials #3)**

The mixed nutrient solution must be distributed to the plants through a series of plastic tubes, connectors, etc.

**Solenoid Valves (see Schematic 1, Materials #4)**

Several types of solenoid valves are available. Most are “normally closed” and, when opened by the controller/timer, allow nutrient solution to flow (most systems do not need pumps, but rely on the pressure of the source water). The main purpose of these valves is to control the water flow to various parts of the greenhouse. If several types of plants are being grown, a separate solenoid valve can be used for each crop. A single valve could be used to irrigate an entire greenhouse, if there is enough water pressure and volume to feed all the plants on the line at one time. Otherwise, the house can be broken down into lanes or different areas, each controlled by its own solenoid valve and timed such that they do not all activate at once.

**Irrigation Controller/Timer (see Schematic 1, Materials #5)**

Several types of controllers/timers are available. A time clock can simply turn “fertigation” (the combination of irrigation and fertilizer with every watering) on and off at set intervals. Simple controllers may have several programs so that different solenoid valves may be turned on/off at different times. More sophisticated controllers may not only be connected to the solenoid valves but to the injectors as well so that EC can be adjusted according to light levels.
Poly Tubing (see Schematic 1, Materials #6)

Most drip irrigation systems use ½ inch poly tubing. At the input end, the tubing is connected to the solenoid valve. At the other end, the tube is either crimped shut or an end cap is attached. The tubing is run down each row of plants. A poly tube punch is used to poke holes in the poly tubing to accommodate the drippers (see below). Punch straight in and pull straight out without excessive movement of the punch in the hole. Excessive movement of the punch in the hole will cause a larger hole than needed and solution can leak around the dripper barb. If a hole is too big or in the wrong position, a “goof plug” can be inserted to seal the hole.

Emitters or Drippers (see Schematic 1, Materials #7)

Several types and sizes of drippers are available. A typical size for a commercial greenhouse use is 0.5 gallons per hour (gph). This allows for better control of the delivery of nutrient solution to each plant and can be fine-tuned depending on the length of each irrigation. Drippers should also be pressure compensating such that they will deliver their given flow rate under a wide range of source water pressures. Note that water pressure must be at least 5-10 PSI for the drippers to work properly. Pressure compensating emitters are also “one way”: the water will only flow through them in one direction. Each dripper has 2 attachment barbs: make sure the input barb is inserted into the poly tubing and the output barb is attached to the drip tubing.

Drip Tubing (see Schematic 1, Materials #8)

This is also known as “spaghetti” tubing because it is relatively thin. Make sure the tubing is securely attached to the output dripper barb (dripper barbs are not all the same size and will require specific sized tubing – the fit should be snug since the plastic of the tubing can expand slightly during warm weather causing leaks). As plants are worked on or leaned and lowered (see below) drip tubing can be detached from the dripper. Therefore, regularly check to make sure that the tubing is connected. (Note: look for areas of wetness and algae growth (green) to find leaks.)

Stabilizer Pegs (see Schematic 1, Materials #9)

Several types are available. A “C” peg is designed such that the tubing is secured within the “C” of the peg. With a “V” type peg, the tubing slips into and is secured between the two sides of the “V”. The purpose of the peg is to position the opening of the drip tube over the growing block (see below) so that the nutrient solution drips onto the top of the block and runs into the bag (root zone) and doesn’t end up on the plastic bag, or the floor, etc. The peg should be inserted into the block or just alongside the block. The tubing should not touch the stem or the top of the block since adventitious roots, that develop from the stem, or roots from the block will grow into the tube and block it, halting solution delivery to that plant.

1 Inch Rockwool Propagation Cubes (see Schematic 1, Materials #10)

The cubes: Rockwool propagation cubes come in 2 basic sizes: 1” and 1 ½”. The cubes are attached on their sides in a pad and can have 70, 98 or 200 cubes per pad. The Rockwool is sterile (no pests or weed seeds), has an excellent water holding capacity and also has good aeration (to provide needed oxygen to the roots.). Each cube is pre-drilled with a planting hole. The pad should be placed in a germination tray with holes and saturated with plain water prior to planting the seeds.
The seeds: The two basic types of “growth habits” for plants are determinant (plants grow to a certain height and end in a flower, eg., bush tomatoes) and indeterminant (plants continue to grow as a vine, putting out leaves and clusters at the growing tip). In order to utilize the vertical height of the greenhouse that has been built, select indeterminant varieties of tomato seeds. Varieties selected should also be bred for greenhouse use and for the region (some varieties do better in cooler climates whereas others do better in warmer regions).

Planting: One seed should be placed into each propagation cube hole. Make sure to overplant in order to account for fast, slow or no germination. A thin layer of fine vermiculite can be sprinkled over the top of the cubes and then sprayed with a gentle mist of water. In order to germinate, seeds require moist conditions (water, not nutrient solution) which can be delivered either from below on a germination table or (less optimum) from above on a mist bench.

Growing conditions: Moderate temperatures (25-26 C or 77-80 F day and night) should be maintained and, if necessary, bottom heat can be used. If the media temperature exceeds 29 C (84 F) there can be an increase in the number of “off plants”. Seeds can be placed in a darkened germination room or in a bright greenhouse and should take 4-6 days to germinate. If germination takes place in a darkened room, make sure to move seedlings into the light as soon as they begin to grow out of the hole. Otherwise, they will be etiolated (stretch, be “leggy” and weak). Bright light will keep the seedlings short, stout and strong. Once the seedlings emerge “fertigation” should begin. A complete nutrient solution can be used with each watering, or a concentrate (ex. 20-20-20 at 2 tablespoons/gallon) can be applied 2-3 times before transplant. If a concentrate is used and is applied overhead with a watering can, gently spray the leaves with plain water to rinse the concentrated solution from the leaves and avoid burning.

3 Inch Rockwool Blocks (see Schematic 1, Materials #11)

Normal transplant: After about 2 weeks (may be longer in higher latitude areas due to cooler temperatures and less light) the seedlings can be transplanted into the 3” (or 4”) Rockwool blocks each of which has a pre-drilled hole of the proper size to accommodate a propagation cube. (Note: larger 3”x6” cubes with two holes each are also available.) The time of transplant is determined by root growth – as the first roots are beginning to appear from the cube the seedlings should be transplanted. This allows for minimal root damage.

Transplant of etiolated (“leggy”) plants: If plants are growing under lower light conditions (higher latitude, winter, etc.) they may be etiolated (“leggy” or longer than normal). In this case, the seedling can be turned upside down and then the shoot curved back up into a “U” so the leaves are again pointing upward. The cube is then inserted into the block. The stem, in contact with the cube and block, will produce “adventitious” roots and the seedling will be shorter and stronger.

Growing conditions: Similar temperatures, as above, can be maintained. Again, either a complete nutrient solution can be used at every watering, or a concentrate can be applied 2-3 times (rinse leaves with plain water after overhead application of concentrated solution). As the seedlings grow they should be spread apart so that their leaves do not overlap. Otherwise, the shading of neighboring leaves could cause the seedlings to etiolate (stretch and become weaker).

The production of “transplants” is an industry in and of itself. In the case of greenhouse hydroponic tomatoes, the separation of transplant production and the growing of mature plants for tomato harvest means that each grower can tailor the growing conditions for their plant’s life stage needs.
**Rockwool Slabs – Or Grow Bags (see Schematic 1, Materials #12)**

Rockwool slabs come in two basic sizes: 36”x3”x6” and 36”x3”x8”. Six inch wide slabs can be planted with 3 transplant cubes (3 plants/slab), whereas 8 inch wide slabs can be planted with 3 sets of 2 transplant cubes (6 plants/slab).

**Slab arrangement and overhead supports:** Arrange the slabs in rows with their centers approximately 5 feet apart. With 6” slabs and 3 plants/slab, run two rows side by side (can run the poly tubing between the two rows). With 8” slabs and 6 plants/slab, run one row of slabs (with the poly tubing running along one side of the slabs) down the row. Overhead, there should be two support cables (make sure the wire is rated for an expected weight of up to 30 pounds per plant). The cables should be 2 feet apart (1 foot each off center of each row). The support string for the plants will be hung from these cables (see below) in a “V” arrangement. Note: the rows in the greenhouse should run north-south to receive maximum, even lighting throughout the day.

**Transplanting onto the slabs:** After another 2 weeks (may be longer in higher latitude areas due to cooler temperatures and less light) the young plants can be transplanted onto the Rockwool slabs. Three to six young plants may be placed on each slab (depending on slab size). Three “X”-shaped slits, equally spaced along each slab, should be made. The slits should be made to accommodate the Rockwool blocks. The slabs should then be wetted with nutrient solution (the stabilizer pegs with drip tubing can be placed in the Rockwool and the fertigation system turned on until the Rockwool is saturated). The flaps of the “X”-shaped slits are then opened outward and the cubes are placed onto the slab such that the Rockwool of the cubes is in direct contact with the Rockwool of the slab. Insert the stabilizer peg with the drip tubing into the block as described above. Cut two 1 inch diagonal slits from the mid-point downward and equally spaced on one side of each slab to allow for drainage.

**Collection methods:** In order to keep excess nutrient solution from contaminating ground water in the vicinity of the greenhouse, several methods can be used to collect the solution after it passes through the slabs. The slabs could be placed in a molded plastic or metal trough and the run-off solution collected at the end of each trough. The slabs could also be placed on 4 inch high styrofoam slabs with the slabs wrapped in heavy-duty plastic film such that a portion of the plastic film, on the side of the slabs with the drainage slits, hangs down forming a pouch through which the drainage solution flows. If the solution is not reused, the system is called “drain to waste” or open. If the solution is collected and reused, the system is called “recirculating” or closed.

**Vine Twine Wound Onto Tomahooks and Vine Clips (see Schematic 1, Materials #13 & 14)**

**The plant support system:** The indeterminate or vining tomato plants must be supported in some manner. Polypropylene twine (with UV resistance) is wound around heavy-duty metal “tomahooks” that are then hung from the metal support cables above the rows. Enough vine twine must be wound onto the tomahooks to equal the estimated final length of the tomato vines. This can be up to 40 feet for vines after 9-10 months and will depend on variety, plant health and environmental/nutrient conditions. Plastic vine clips (in various colors including black, green and white) have a hinge that clamps around the vine twine and encircles the tomato vine. The clips should be placed under a sturdy leaf (like a crutch) and at about 1-foot intervals as the plant grows upward. Clips should not be placed closer than 6 inches from the apex of the plant as the stem in this region is still elongating.

**Leaning and lowering:** Since the tomato vines can reach up to 40 feet in a season, but the typical wire supports in a greenhouse are usually only 10-16 feet, the vines will have to be
lowered as they grow. They must also be leaned so that a ninety degree bend at the floor level does not occur which could result in a cracked stem and a dead plant. (Note: if a stem is cracked, even most of the way through, it can be aligned and tightly wrapped with electrical tape and even splinted. If enough tissue is intact the stem will heal – the plant may wilt for a few days.)

Initially, when the vine twine is attached to a young plant, position the tomahook on the wire, not over that plant but, over the plant on the right (or left – choose one side or the other for all plants). This will cause the plant to bend to the right from the start. Consequently, each row is made up of 2 rows of plants with 1 support wire over each plant row. When viewed from one side, the closer side of this double row will be leaning to the right and the farther row will be leaning to the left. When seen from above, the plants will be leaning in a counter clockwise direction.

When the plants grow up the vine twine and reach the support cable, the twine is unwound (lowered) and the tomahook is moved to the right one space (leaned). Leaning and lowering must always be started at a point in the row where there is a space to the right. The first plant is leaned and lowered into that open space and the process is continued “backwards”, always leaning and lowering into the newly created empty space.

The plants should not be lowered more than 2 feet from the support cable. Note that since flower pollination and fruit set is very sensitive to variations in temperature, the temperature sensor for the greenhouse should be positioned at the same height as the open flowers. As the plants grow the sensor should be raised until the sensor is about 2 feet from the support cable. As the plants are leaned and lowered, this will be an average height for the open flowers.

**Sucker pruning:** To maintain the plant as a single stem vine, side shoots (suckers) must be removed. These suckers grow from the axils of the leaves (the top of each leaf where it joins to the stem). They are aptly named since they “suck” nutrients from the main growing regions – the apical meristem and the developing fruit. Suckers are easily broken off the plant and should not be cut since this can leave an open wound for disease to enter. Note that there are several side shoot or sucker buds in every leaf axil, and that new suckers can appear in leaf axils where suckers were previously removed (even along the base of the vine).

**Leaf pruning:** As the tomato vine grows, the lower, older leaves begin to senesce and must be removed. The leaves must be popped off at the connection point of the leaf to the stem – the abscission zone. This is most easily done in the morning when the plant is turgid. The leaves must not be torn off or cut off as this leaves a slow-healing wound at an unnatural break point through which diseases can enter.

During the winter, especially, relative humidity can rise in the greenhouse to close to 100% which can promote diseases such as *Botrytis* which occurs mainly in the stem. Leaf pruning reduces the leaf area and therefore the transpirational surface area which will reduce the amount of water vapor introduced into the greenhouse by the plants themselves. Leaf pruning also increases air circulation around the lower stems, reducing the chances of diseases.

Leaf pruning can also help maintain the balance between vegetative and reproductive (sometimes referred to as generative) growth in the plant. If many leaves are removed the nutrients/photosynthates will be shunted more toward the developing fruit – the plant is pushed toward reproductive growth. When many leaves are left on, the plant is pushed toward vegetative growth.
J-Style Truss Hooks (see Schematic 1, Materials #15)

The cluster or truss: The main reason for growing the tomato plants in the first place is for the tomato fruit. The fruit is borne on a cluster or truss with 1 to as many as 14 fruit to a cluster. The flowers are complete containing both male and female parts as well as sepals and yellow petals.

Pollination, fertilization and the use of bees: Tomato flowers can set fruit on their own pollen and in nature the wind is enough to move the plants and shake the pollen from the male anthers to the female stigma. The pollen grains then germinate, grow down the style and into the ovary where fertilization takes place. If fertilization is not complete problems can occur, such as cat facing, making the fruit non-marketable. Typically, in a commercial greenhouse, bumble bees are used for pollination. Bee hives can be purchased from various sources and placed in the greenhouse. The bees are not normally aggressive but should be placed away from high traffic areas. The bumble bees latch onto the flowers and “buzz pollinate” by shaking the flowers. Since this latching on causes brown bruise marks on the anther cones, flowers can be checked periodically for evidence of bee visitation. Since hives only last 1-3 months, less than 80% visitation may indicate a declining hive and the need to order another.

Cluster clipping: Since the tomatoes can weigh a half a pound or more, cluster clips (of several designs) are available to support the clusters. The plastic J-style cluster clip has a curve at one end that cradles the truss stem and one or two clamps at the other end that snap on to the vine twine. The cluster clips should be placed so as to support the entire cluster.

Cluster pruning: The goal of the commercial grower is to produce a consistent quality and quantity of fruit for the market. The quality of fruit can be determined by the initial variety selected, the nutritional regime and other environmental factors. The quantity of fruit, however, can be controlled by cluster pruning. During periods of high light (summer, early fall, late spring) most beef type tomato varieties can maintain an average of 5 fruit per cluster. However, with the lower light levels of winter, and the need for greater leaf pruning to reduce transpirational surface area (which also reduces photosynthetic leaf area), most beef type tomato varieties can only maintain an average of 3 fruit per cluster. If more fruit is allowed to set, each fruit can be correspondingly smaller in size. Cluster pruning is also used to remove defective fruit (boats, cat face, blossom end rot, etc.). Finally, cluster pruning in conjunction with leaf pruning can be used to help maintain a balance between vegetative and reproductive growth. If more fruit is left on, the plant will tend more toward reproductive growth. If more fruit is removed, the plant will tend more toward vegetative growth.

Harvesting: Beef type tomatoes should be harvested 2 to 3 times per week. The color at which the fruit is picked depends on the time between picking and sale to the consumer. The longer the tomatoes are allowed to ripen on the vine, the better the flavor. The tomatoes are removed at the “knuckle” attachment point to the cluster stem by placing the thumb on top of the knuckle, cradling the fruit with the rest of the hand and pressing down slightly with the thumb while pulling up with the hand. The green stem and sepals should remain on the fruit to give it that “home grown” appearance. Do not pile fruit on top of one another as the stiff stems can poke neighboring fruit. Fruit is usually sorted and graded mechanically. Number 1 fruit are perfect or near so and are above a certain weight. Number 2 fruit can have minor defects or will be smaller in size. Culls are fruit with major defects or fruit that is extra small.

Cluster tomatoes, or tomatoes on the vine (TOV’s) are varieties where the entire cluster is harvested as a unit. These have to be sorted by hand and are usually packaged in net bags.
**Schematic 1: System Design:** Injector system with bag culture

**Introduction:** This system is
- **Active (requires electricity and pumps and/or injectors to operate)**
- **Open (the nutrient is “drain to waste” or closed – nutrient is recycled)**
- **An aggregate system (roots grow through an aggregate medium)**
- **Best for larger plants (indeterminant tomatoes, peppers, cucumbers, etc.)**

**Materials:**
1. Water source (make sure water is of good quality (low EC) and quantity).
2. Injectors with nutrient reservoirs.
3. PVC pipe, connectors, elbows, etc.
4. Solenoid valves with appropriate plumbing and electrical connections.
5. Irrigation controller/timer (wired to solenoid valves, and sometimes the injectors).
6. Poly tubing (for drip irrigation).
7. Emitters (drippers) – typical is 0.5 GPH CNL, pressure compensating.
8. Drip (spaghetti) tubing (for drip irrigation).
10. 1” Rockwool propagation cubes (transplant into 3” or 4” blocks or directly into bags).
11. 3” or 4” Rockwool blocks (optional if planting 1” cubes directly into bags).
12. Rockwool slabs, or grow bags fill with perlite, coconut coir, etc.
15. J-style truss hooks (cluster clips).
Reference Material:


Web Site: http://ag.arizona.edu/ceac/
The University of Arizona, Controlled Environment Agriculture Center
Information on teaching programs, research (including papers) and extension work.
Under CEA Basics, see the PLS 217 class manual: Introduction to Hydroponics and CEA.