Controlled Environment Agriculture
A Pilot Project

by
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CONTROLLED-ENVIRONMENT AGRICULTURE

A Pilot Project

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CHAPTER I

INTRODUCTION

Recent advances in the field of plant science have made significant increases in plant productivity a reality. The ability to control the growing atmosphere through use of advanced lighting techniques, CO_2 supplementation, refrigeration, and heating controls has made this possible. To what extent such levels of environmental controls are economically feasible, however, is a major consideration.

The advantages of intensive, controlled-environment, agricultural production centers are numerous. The major advantage of a totally controlled growing atmosphere is the ability to produce vegetable crops year around with no dependence on climatic conditions. This is particularly important in arctic regions where good quality vegetables can be obtained only by importing them at high cost. In Alaska, for example, a state one-fifth the size of the 48 conterminous United States, significantly less than one-half the fruits, vegetables, and grains consumed are produced locally due to growing-season limitations. Because of the remoteness of many areas of the state from major vegetable-producing areas, quality vegetables, particularly highly perishable salad vegetables, are available only at a substantially increased cost. Control of growing conditions opens the possibility of greatly expanding local vegetable production, thus providing high-quality vegetables for local markets on a regular, year-round basis.

The controlled-environment agricultural (CEA) project discussed in this report was first conceived for the Wildwood Air Force Station in Kenai, Alaska, in 1972. The region contained high unemployment and a U.S. Air Force Station that had just closed. The Kenai Native Association, Inc. (KNA), was to take possession of the Air Force Station through land transfers associated with the Alaska Native Claims Settlement Act, and this corporation was interested in expanding business and employment opportunities for local people. The University of Alaska Agricultural Experiment Station (AES) contacted KNA to determine if it had a facility which might be adaptable for use in a research and development program in controlled-environment agriculture. It was determined that such a facility was available. Subsequently, AES and KNA contacted the General Electric Company (GE) in Syracuse, New York, to determine its interest in such a project. GE had extensive background in lighting technology and environmental control systems and the engineering capability to develop a total system for CEA production. It was agreed that GE would provide technological expertise and AES would provide horticultural and economic expertise for the growing and marketing of a variety of salad crops. KNA would manage the project, employ the nontechnical people, and provide the building.

The Wildwood site was selected because it contained two buildings which were thought to be well suited for CEA production. One building would provide sufficient inside space for a 1/4-acre pilot production plant, nine small research modules, a laboratory, offices, a training area, and space for preparing the crop for shipping. A second building near the first contained three diesel generators which were to be converted to natural gas to provide power for the production facility.

Kenai is located near one of the largest natural-gas fields in Alaska and this gas was expected to be a source of cheap fuel for the project. The community is located near the largest city in Alaska, Anchorage, making it convenient to receive supplies necessary for the project and to market produce after the research and demonstration period were completed.

The CEA approach was based on research efforts at the University of Arizona's Environmental Research Laboratories on vegetable production in desert regions; experiments in the Phyto-Engineering Laboratory of the Agricultural Research Service, U.S. Department of Agriculture at Beltsville, Maryland; and modular growing experiments conducted by GE at Syracuse, New York. Contributions were also made by AES personnel who had conducted related research in their own greenhouse facilities.

The primary objectives of the Kenai CEA project were 1) to create employment and provide training in CEA production; 2) to evaluate the economic feasibility of CEA; 3) to determine the environmental conditions to produce the best crop per dollar cost; and 4) to establish a data base for CEA projects elsewhere.

This report describes the experimental program for the CEA project. This will include the experimental methods used in both horticultural and economic research efforts. Next the outcome of horticultural research will be delineated for both the research modules and the pilot plant. All studies are discussed as they occurred chronologically. The fourth chapter includes the results of the economic studies associated with the CEA project. Finally, conclusions, implications, and recommendations are made concerning the entire research and demonstration effort. Throughout the text, significant issues have been emphasized to establish the directions taken during the project and to point the way in which future efforts may lead.

CHAPTER II

EXPERIMENTAL PROGRAM

HORTICULTURAL RESEARCH METHODS

The purpose of an experimental program for controlled-environment plant growth was to evaluate the relationship between a series of specified environmental variables and plant-growth response (yield, quality, etc.) for several salad vegetable crops. To accomplish this required manipulation of the principal plant-growth factors, light, temperature, carbon dioxide (CO_2), and nutrition, in order to obtain yield and quality data. Both module and pilot-plant research methods are presented in this section.

Modules

Variables Controlled: Nine, large, walk-in controlled-environment chambers with a usable space of 19.7x10.5x10.5 feet were installed according to specifications supplied by GE (KNA, 1973; Rauhala, 1973; and Scott, 1974). Each module contained four plastic-lined "grow beds," 4.4 inches deep with a total area of approximately 136 square feet. An artist's concept of the modules, bed placement, and tomato, cucumber, and lettuce crops are shown in Figures 1 through 6.

Soil-heating cables were imbedded in the peat-vermiculite growing mix to hold the "soil" temperature constant. The modules were also equipped for the control of CO_2 level, air temperature, humidity, and daylength. Light intensity and quality were varied by changing the number and ratio of the two lamp types—high-pressure sodium and metal halide.[1] Nutrient levels and soil temperatures for each of the crops considered were not included variables in the statistical model. The range of each of the environmental variables is shown in Table 1.

Table 1: Ranges of Environmental Variables Used in the Modules

Environmental Variable	Range	Unit
Carbon dioxide (CO_2)	900-3000	parts per million (ppm)
Air temperature—day	70-85	degrees fahrenheit (°F)
Air temperature—night	60-85	degrees fahrenheit (°F)
Relative humidity	60-85	percent (%)
Light intensity	1000-4000	footcandle[a]
Daylength	12-24	hours
Light mix—HP Sodium:Metal Halide	1:1-5	

[a] Illuminance levels (footcandles or lux) are used in this report because of the common usage of this unit in the industrial lighting industry. It is acknowledged that plant physiologists prefer irradiance units (radiant flux) in microeinsteins per square meter per second (E/m^2/sec.).

General Plant Culture: Two, distinctly different cultural systems were utilized in the modules—container or bed culture in nonsoil media, usually a commercial peat-vermiculite mix, and trough culture by the so-called nutrient film technique (NFT) credited to Dr. Alan Cooper (1974). Early work was accomplished in pots and beds. A shift was made in the modules to a hydroponic method of growing in PVC pipe. This phase of the project closed in December, 1975. Throughout 1977, the modules were used as a nursery for the pilot plant, using the NFT system exclusively. With both systems, seed was germinated in prepared "soil blocks" —Jiffy 7s, BR 8s, or Kys Kubes.

Plant Nutrition: Nutrition of the various crops in the modules during the pot- or bed-culture phase was accomplished both by means of prescribed nutrient formulas applied through several GEWA fertilizer proportioners[2] using a Chapin Watermatics distribution system[3] and by means of manual plant applications of nutrient supplements. Formulas were based on the type of crop, the experiment being conducted, and the general response of the plant. Nutrient formulas were adjusted from time to time in response to apparent nutritional problems. In some cases hand applications

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[1] Lamps were supplied by GE, as Lucalox, and Multi-vapor, and were used in GE Duraglow fixtures with an 18-inch, faceted, open reflector.

[2] GEWA imported through Herman Wirth, sold by Harry Sharpe and Son, Seattle, Washington.

[3] Chapin Watermatics, Inc., 368 N. Colorado Ave., Washington, D.C.

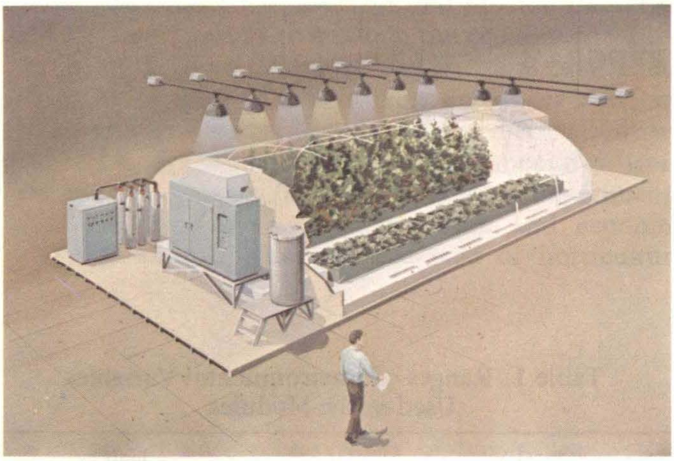

Figure 1: An artist's concept of the research modules.

Figure 2: Cucumber and tomato crops in early stages of growth in the modules.

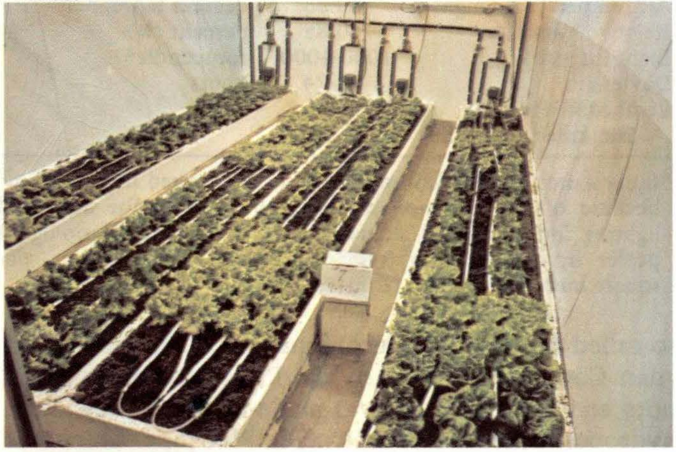

Figure 3: A lettuce crop in the modules.

Figure 4: A lettuce crop in the modules showing the spaghetti-tube watering system.

Figure 5: Buttercrunch lettuce just prior to harvest.

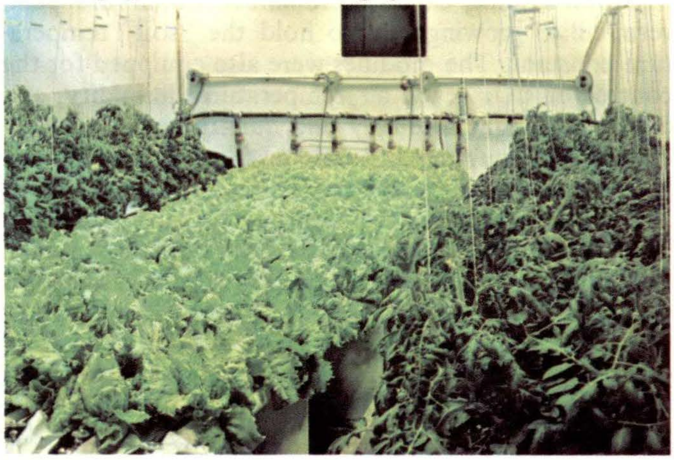

Figure 6: Tomatoes and lettuce were grown in the same environment in several tests.

Table 2: Typical Levels of Nutrients (ppm) Supplied toYoung (less than 3 clusters set) and Older Tomato Plants in Pot Culture—1974-1975

Element	Young Plants	Older Plants
N	92	208
P	80	80
K	283	283
Ca	0	165
Mg	54	54
Fe	8	8
Mo	0.03	0.03
S	73	73
B	0.6	0.6
Cu	1.3	1.3
Mn	3.4	3.4
Zn	1.9	1.9
Na	0.3	0.3

of various formulas were used, and in several lettuce experiments, slow-release fertilizer was incorporated into the media. Typical levels of nutrients for nonbearing and bearing tomatoes in pot culture are given in Table 2.

In mid-1976, the decision was made to convert the entire facility, both modules and pilot plant, to Cooper's NFT system with separate installations of equipment for each area. The modules were used as a nursery. Four to six preformed, soft plastic troughs were placed side by side on a 1% inclined plane. Seed was germinated in blocks (Jiffy 7s, Kys Kubes) in the troughs and nutrient flow increased as the plants grew. After periodic changes, the final nutrient formula for the modules was established and is shown in Table 3.

It was initially planned to carry out all the plant and media analyses weekly with on-site personnel and equipment. It was found to be necessary, however, to consult with other laboratories such as Soil and Plant Lab, California; Rutgers University, New Jersey; Cornell University, New York; Ohio State University, Hydro-Gardens, Inc., Colorado; and Marr Waddoups, Washington, for sample analysis to augment those conducted on-site.

Crops Produced: Though a number of crops could be considered potential candidates for CEA production, only three, tomatoes, cucumbers, and lettuce, were selected for primary attention in the modules. Exploratory trials were conducted with radishes and melons. Species and cultivars grown in the modules are indicated below.

Lettuce:	Bibb—Massa, Deciminor, White Boston, Domineer Crisp head—Minilak[illegible], Ithaca, Fulton Leaf—Grand Rapids: Romaine—Parris Island Cos
Tomatoes:	Vendor, Tropic, Hawaiian Selection, N-89, Jetstar
Cucumber:	LaReine
Radish:	Cherry Belle (limited test)
Melon:	Ha-Ogen (limited test).

Experimental Design: A great deal of attention was given to design of experiments prior to the initiation of actual research in the CEA modules at Kenai. Original plans called for testing the plant-growth

Table 3: Nutrient Formula for Tomato Seedlings[a]

Salt	(g/1000L)	g/550L	(ppm$_e$)[c]	Concentrate[d] (g/70L)	Nutrient
Calcium Nitrate	448.3	246.5	65 (N)	3138.1	
			85 (Ca)		1
Calcium Carbonate[b]	298	159.0	50 (Ca)	2086.0	
Potassium Nitrate	260	143	100 (K)	1820	
			35 (N)		
Mono Potassium Phosphate	355	195.2	80 (P)	2489	
			102 (K)		
Sequestrene 330 Fe	22.2	12.2	2 (Fe)	155.4	
Manganous Sulfate	1.53	0.85	0.5 (Mn)	10.7	2[e]
Zinc Sulfate	0.055	0.03	0.02 (Zn)	0.54	
Copper Sulfate	0.16	0.088	0.04 (Cu)	1.1	
Boric Acid	3.428	1.89	0.6 (B)	24	
Ammonium Molybdate	0.092	0.05	0.05 (Mo)	0.64	
Magnesium Sulfate	324.3	178.4	32 (Mg)	2270	

[a] A low-nitrate nutrient mix for plants to first fruit. This is a nursery formula for cucumbers, tomatoes, and lettuce.
[b] Calcium chloride (flake) if calcium carbonate is not available.
[c] Parts per million of the element.
[d] Concentrate solution is used at the rate of 1 part to 100 parts H_2O.
[e] Add 150 ml phosphoric acid/70L to nutrient concentrate 2.

response of 6 environmental variables at 4 levels simultaneously (Feder and Hahn, 1973). These were CO_2, light intensity and quality, day and night temperature, and soil temperature.

Plant scientists and others proposed a plan which involved five factors: CO_2, light intensity and quality, and day and night air temperature (KNA, 1973; Lewis, 1974a; Scott, 1974; Vinzant, 1974a; Vinzant, 1974b). Daylength, humidity, soil type, and nutrition were to be controlled at prescribed levels. Four crops: cucumber, lettuce, radish, tomato, were to be included in the program which was to run for 7 growing seasons of 11 weeks each or approximately 18 months in the 9 modules.

The plan was implemented in mid-1974. By early 1975, two runs of lettuce and one run of tomatoes and cucumbers had been completed (KNA, 1977). Serious technological and horticultural problems were encountered in these trials. Variations between nominal set points and actual values were excessive (Table 4). Temperature control was particularly troublesome; cooling water in the refrigeration coils became clogged with red algae. Soil temperature and humidity varied widely; CO_2 varied to a lesser degree.

After these first runs of the experimental trials, the plant physiologists noted that some of the test points chosen were "nonsense points" (obviously intolerable for plant growth). After a review of results of the initial runs in early 1975 (Lewis, 1975a), it was concluded that the original objectives of the program could be better met by a revision of the experimental design for the modules. While it may have been desirable to develop an experimental program to examine the effects and interactions of all the known experimental factors, it was necessary to keep the program within physically and financially manageable limits.

The new program initially placed greater emphasis on the most cost sensitive environmental factor, light (intensity and duration), and on the interaction of temperature and CO_2 concentration with light. Lettuce was used for these studies. Other studies were conducted on the response of tomatoes to light intensity and duration. Minor emphasis was given to cucumbers in the modules since they seemed to respond favorably to conditions of the pilot plant.

Data Collection System: For each test cycle (module run), 5,749 measurements were taken (Table 5, next page). File and record systems were used which were keyed to general statistical analysis formats (Lewis, 1975a). Files included in the record system were:

1. Environmental Data:
   Environmental parameters and specifications and measurements.
2. Test Data:
   Deviations from environmental parameters and specifications recorded in 1, above.
3. Pre-planting Data:
   Data concerning the plants in the seed and germination area and the nursery.
4. Specification Data:
   The specific plant location after movement from the nursery and all transplant data after that movement until the plant reached its final location.
5. Test Data:
   Data on the plant's growth and general comments after the plant reached its final location.
6. Yield Data:
   Data on the final product including quality and yield.

Table 4: Summary of Module Environmental Conditions

	Lighting (fc)		Air Temperature (°F)								Soil Temp. (°F)			CO_2 (ppm)		Relative Humid. (%)
	Nominal[a]	Recorded	Nominal		Recorded						Recorded[b]			Nominal	Recorded	Recorded[b]
			Day	Night	Day			Night								
Module					Max	Avg	Min	Max	Avg	Min	Max	Avg	Min			
1	1000	1064	72	65	90	70	67	80	68	63	74	70	67	1500	1350	80
2	2000	2698	86	86	96	82	79	92	83	60	91	85	80	2500	2200	72
3	2000	2394	72	57	77	72	60	73	67	61	74	70	64	2500	2100	75
4	2000	2850	72	72	80	77	70	80	73	70	80	76	74	1500	1600	80
5	3000	3306	72	72	77	72	68	80	70	60	106	80	70	2500	2000	70
6	3000	3344	86	71	88	85	80	85	70	66	114	85	68	2500	2250	68
7	2000	not meas.	72	57	78	70	63	73	70	62	78	74	66	2500	2000	80
8	3000	3800	86	86	94	84	81	90	84	68	82	78	76	1500	1300	70
9	2000	not meas.	86	71	93	84	63	89	75	69	73	72	65	1500	1400	70

[a] Existing in theory only, not values actually measured.

[b] No nominal setting was specified.

Table 5: Measurements Recorded in the Modules

Measurement	Percent Measured	Crops				
		Radishes	Lettuce	Tomatoes	Cucumbers	Total
Number of Samples	100	576	302	36	24	938
Number of Fruit	100	–	–	30	30	60
Days to Emergence	100	1	1	–	–	2
Days to Anthesis	100	–	–	1	1	2
Days to Harvest	100	1	1	1	1	4
Height at 3 Clusters	100	–	–	1	–	1
Fresh Weight Roots	100	576	–	–	–	576
Dry Weight Roots	10	60	–	–	–	60
Density Roots	10	60	–	–	–	60
Fresh Weight Tops	100	–	302	–	–	302
Dry Weight Tops	10	–	30	–	–	30
Fresh Weight Fruit	100	–	–	1,000	720	1,720
Dry Weight Fruit	10	–	–	100	72	172
Length of Fruit	10	–	–	–	72	72
Number Fruit Set	100	–	–	36	24	60
Grade	100	–	–	1,000	–	1,000
Flavor	10	60	–	200	140	400
Firmness	10	–	–	200	–	200
Core Study	10	–	30	–	–	30
Other Quality	10	–	60	–	–	60
TOTAL						5,749

Information other than that available from the formal data system was recorded. These categories were a pictorial record of plant growth, leaf analysis, and fertilizer amounts, types, and frequency of application. The role the data from the research modules played in meeting the overall CEA objectives is shown in Figure 7 (page 9).

Pilot Plant

Environmental Parameters: The original CEA research plan called for a series of experiments in the modules which would help to develop the optimum economic "set-points" for the pilot plant. Due to the problems concerning module performance and the need to begin crop production, a beginning estimate of environmental conditions for a group of plant types–lettuce, radishes, cucumbers, and tomatoes–was developed as follows:

Temperature: day 75°F, night 65°F.
Humidity: 70%.
CO_2: 600-1000 ppm.
Light: a 3:1 mix of 1000 watt (W) high-pressure sodium and metal halide luminaires, mounted at a spacing of 5.5 x 5.5 ft., providing an illumination of about 2000 foot candles at floor level.
Day length: 14 hours average.

Slight modifications were made throughout the course of the project. A pictorial review of the pilot plant is given in Figures 8 through 25 (pages 8, 10, and 11).

Types of Research Conducted in the Pilot Plant: In the initial project plan, experimentation on optimum cultural conditions in the modules was to be applied in the 1/4-acre pilot plant, which was in turn designed to produce economic data related to the efficient use of management, labor, and other production inputs. However, because there were technological problems with the modules and because space was made available in the pilot plant, it was used for cultivar and spacing trials of tomato, radish, pepper, eggplant, sweet corn, and turnip crops. In addition, there was one study of media and nutrient adjustment designed to control a widespread blossom-end rot (BER) problem.

Cultural Conditions: During 1974 and 1975, the larger plants, e.g. tomatoes, cucumbers, melons, peppers, and eggplant were grown in 5-gallon pots of various commercial "soil" mixes containing peat with vermiculite or perlite and other additives to balance pH and provide some nutrients. Crops such as lettuce and radishes were grown in ground beds of the same media. Based on the composition of the initial mix, various nutrient formulas were applied with GEWA propor-

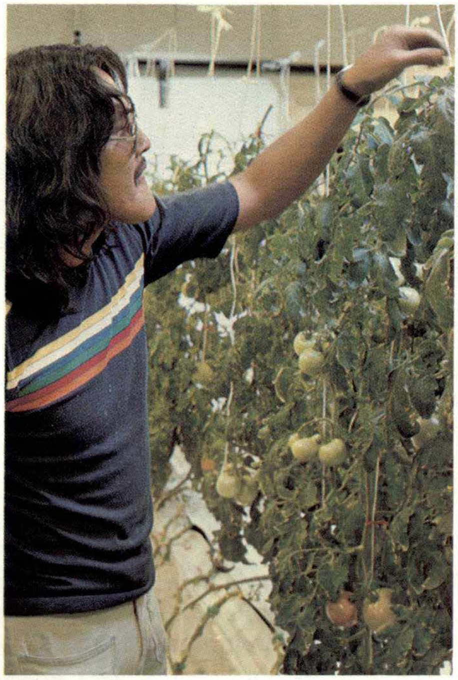

Figure 8: Harvesting the tomato crop in the pilot plant.

Figure 9: A view of the tomato variety Vendor.

Figure 10: An overall panorama of the lighting in the pilot plant.

Figure 11: The nursery was located in the pilot plant during the pot culture phase.

Figure 12: The cucumber and tomato crops were grown in the same environment.

Figure 13: Laborers in the pilot plant performed each task required for plant production.

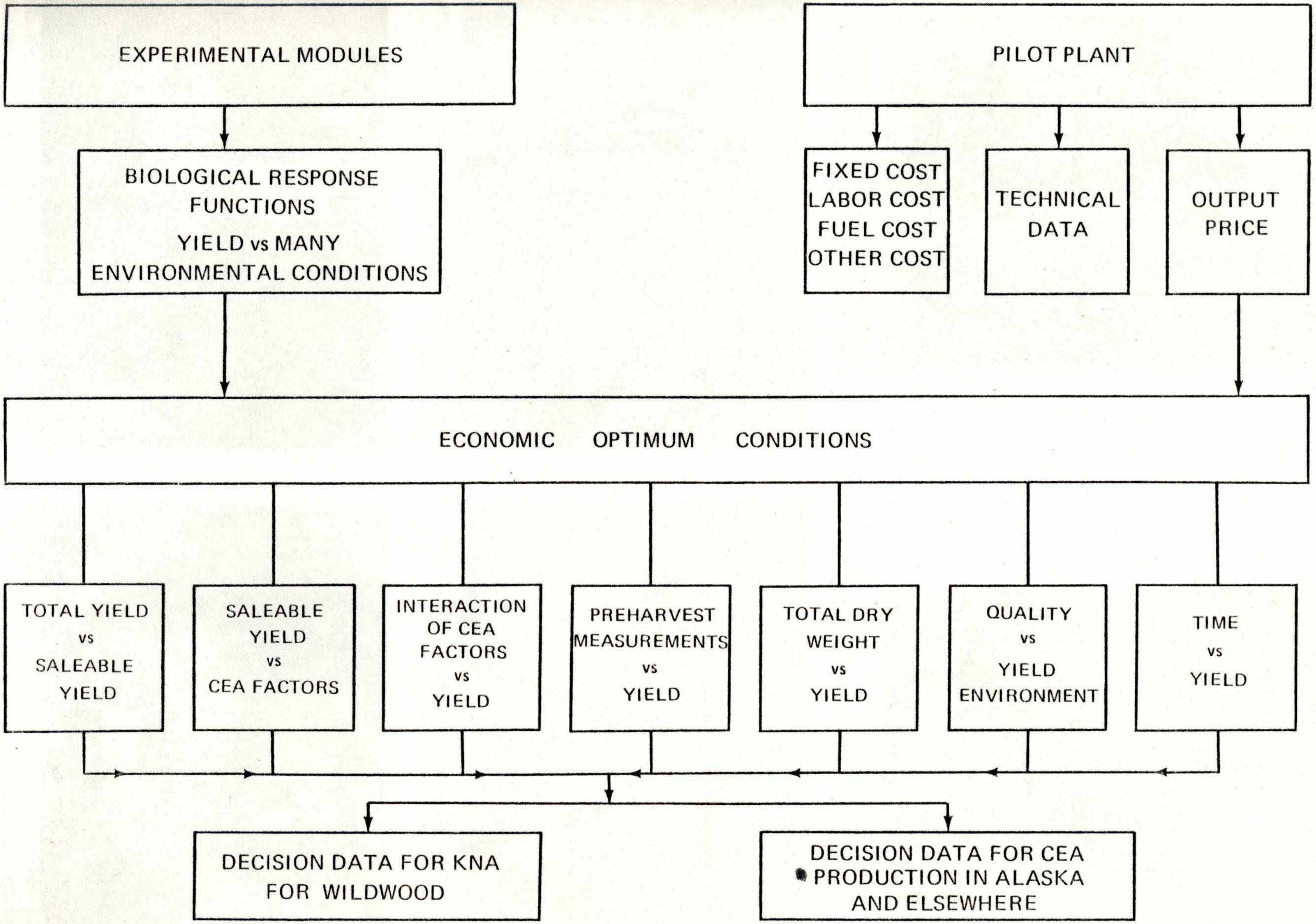

Figure 7: CEA Economic Data Flow Diagram.

Figure 14: The cucumber crop was rotated as seen from the young and more mature plants.

Figure 15: The variety Femdan at a maturity level of two months.

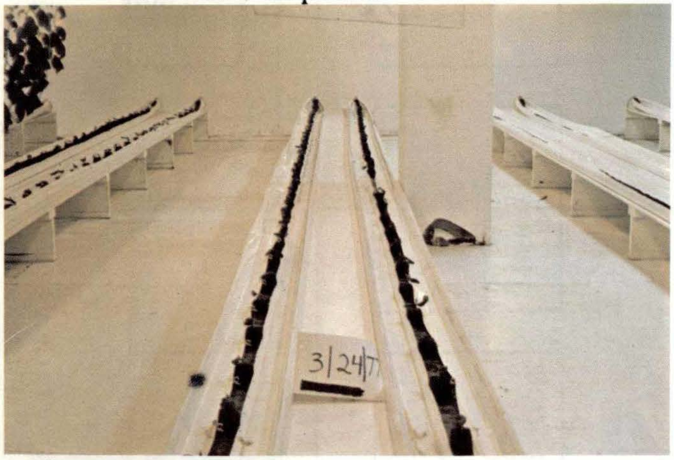

Figure 16: Seedlings were placed directly into the pilot plant from seed in some trials.

Figure 17: In other trials, seedlings were germinated and grown to the first leaf stage in a nursery.

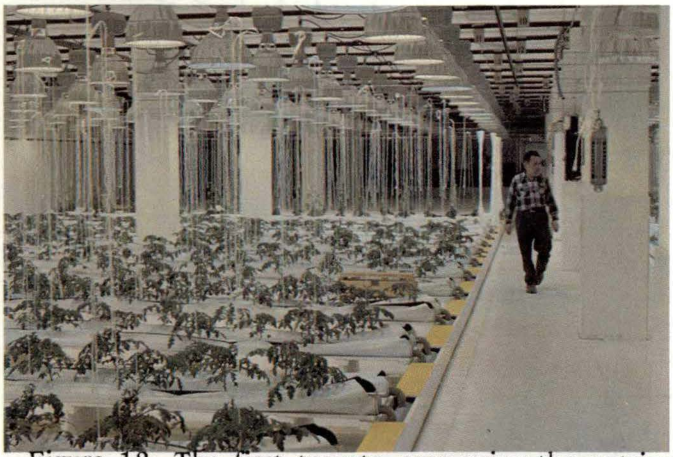

Figure 18: The first tomato crop using the nutrient film production technique.

Figure 19: Use of the nutrient film canals allowed a high degree of cleanliness to be maintained.

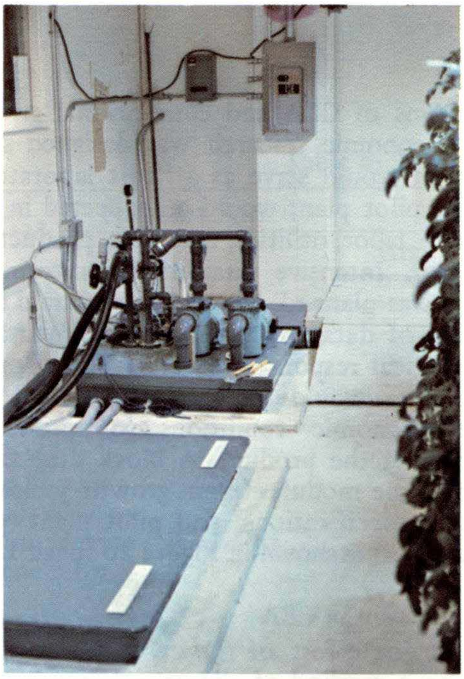

Figure 20: The tanks used to pump nutrients through canals in the pilot plant.

Figure 21: Seedlings were supported by twine tied directly to the canals.

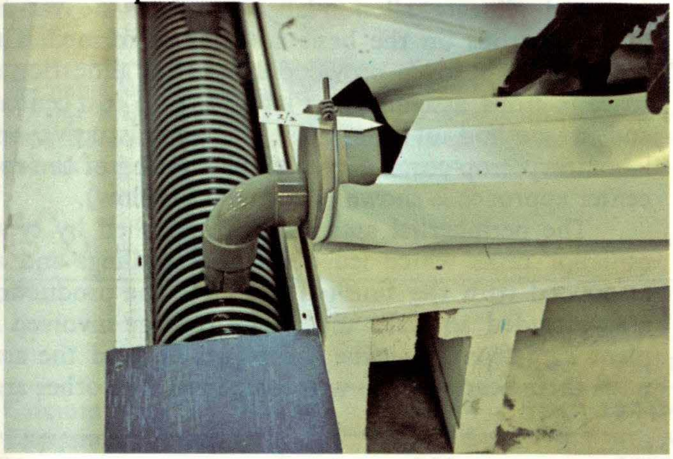

Figure 22: Nutrient flowed out of the canals into the main drain system.

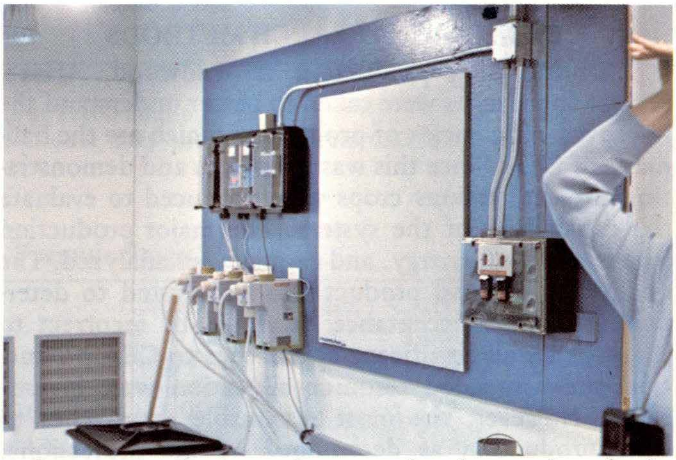

Figure 23: The control system for the nutrient feeder tanks.

Figure 24: A tomato root system showing the canal and absorbant mat at the base of the canal.

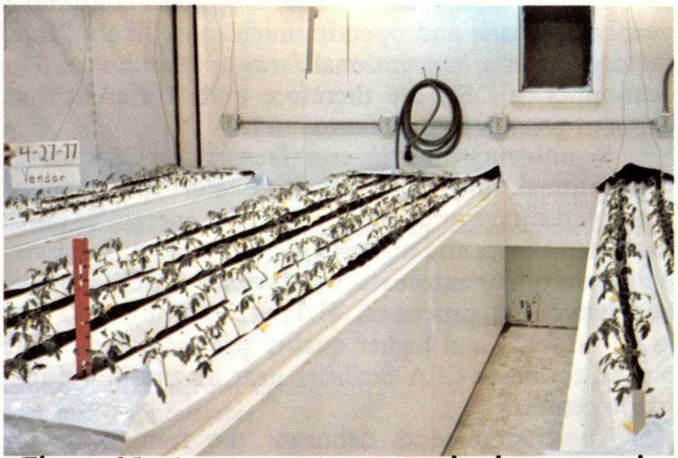

Figure 25: A young tomato crop in the nursery just prior to placement in the pilot plant.

tioners through a Chapin system with individual "spaghetti" tubes in each container and at random on the bed. Supplements were applied as needed through a portable 2-gallon GEWA which could be connected to the water lines at intervals throughout the plant. Nutrient formulas were varied somewhat throughout the 1974-75 period according to type and age of plant, photoperiod, and nutritional problems as shown by leaf and media analysis. A typical formula for bearing plants is given in Table 6 (next page).

In March of 1977, after more than a year of shutdown, the entire pilot plant was converted to the NFT system. The grower-manager initially used nutrient formulas supplied by Cooper (1974), but soon found that tomatoes, in particular, responded better to a gradually increased nitrogen supply as the fruit load increased, Tables 7, 8, and 9 (pages 13, 14). The system was designed such that half the pilot plant (blue side, B) received water and nutrients from one set of tanks and pumps and the other side (yellow side, Y) from another set. In this way, two different formulas were possible.

ECONOMIC RESEARCH METHODS

During CEA production at Wildwood, Alaska, several approaches were taken to better understand the improved efficiencies of production which are the hallmark of CEA. Since this was a research and demonstration project, various crops were produced to evaluate the capabilities of the system. The major production inputs of labor, energy, and capital were analyzed. The quality of the end product was also tested to determine consumer acceptance. It would be incorrect to suggest that all significant approaches to CEA production and associated resource allocation were investigated. However, the most reasonable approaches to CEA production as determined by the professional people involved were considered. The economic feasibility analysis was based on this determination.

A CEA facility can produce crops on a continuous year-round basis and operate much more like a "food factory" than a conventional farm or greenhouse. The economics of CEA are therefore quite different than those of greenhouses or farms.

Significant shifts in cost factors for CEA versus conventional forms of agriculture are: 1) the much larger percentage of operating costs for energy, 2) much lower land costs and higher equipment costs, 3) greater opportunity for automation of the entire CEA growing and harvesting processes, 4) lower growing risks and more uniform and higher quality produce, and 5) the option to locate CEA facilities near or within a population center.

These statements delineate the framework for studies considering production and market analysis and comparisons of CEA and conventional growing techniques. Economic research was designed so that the pilot plant would serve as a "cost laboratory." Data from the pilot plant would be collected in five major categories: labor, utilities, materials, production yields, and waste. Intensive quarterly monitoring of each category was planned. The modules would be used for collection of data concerning environmental variables and biological response variables. The pilot-plant and module data would be combined to determine the feasible economic conditions for production and marketing of the product. A block diagram for data flow from the modules (plant growth, yields, and environmental specifications) and pilot plant (production cost and sales) is shown in Figure 26 (page 15).

Cost Allocation in CEA

A major effort of the economic studies was to determine a method of allocating costs to the various crops which would consider the different stages of production: nursery, fruit production, packing, and grading, and allocate all non-labor costs to the various different crops on the basis of labor performed. This cost-center approach provided a basis for allocation of space to crops, assignment of labor tasks to cost centers, and a method of allocation of administrative and laboratory crop costs. A graphic illustration of the cost center approach is shown in Figure 27 (below).

The peripherhal area was distinguished by types of labor tasks which led up to the seedlings and all associated with the finished product. The production area included all tasks and square footage involved in plant care from the time the plants entered the area until their bearing stage was completed. The other area

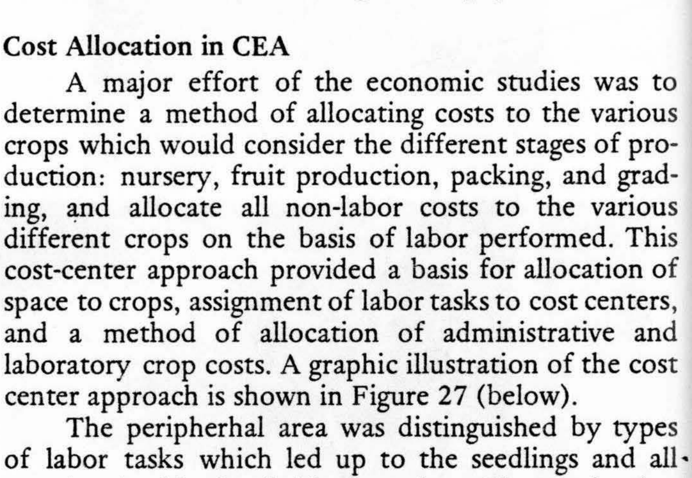

Figure 27: Cost centers grouped into three major cost areas.

Table 6: Typical Nutrient Formula for Pot Culture[a]

Nutrient Formula		Nutrients Supplied (ppm)		
	Grams[b]	Element	Young Tomatoes	Old Tomatoes Cucumbers
GEWA NO. 1[c]				
Magnesium Sulphate	3,500	Mg	54	54
($MgSO_4.7H_2O$)		N	92	208
Potassium Phosphate	2,000	K	283	283
(KH_2PO_4)		P	80	80
Potassium Nitrate	3,200	Ca	0	165
(KNO_3)		Fe	8	8
Ammonium Nitrate (NH_4NO_3)	400	Mo	0.03	0.03
Sequestrene 330	300	S	73	73
		B	0.60	0.60
Peters STEM	250	Cu	1.30	1.30
(Soluble Trace Elements)		Mn	3.40	3.40
Ammonium Molybdate	0.5	Zn	1.90	1.90
		Na	0.30	0.30
GEWA NO. 2[c]				
Calcium Nitrate $Ca(NO_3)_2$	4,650			

[a] Hemphill Memo, July 21, 1975.

[b] Grams of chemical per 15 gal. (57 liter) injector load, applied to plants at 1:100 dilution.

[c] Tomatoes received 600 ml. and cucumbers 700 ml. from GEWA No. 1 once daily and 200 ml. from GEWA No. 2. Young tomato plants with less than 3 clusters set received no $Ca(NO_3)_2$.

Table 7: Tomato Plant Formula Stage 2[a]

Salt	g/1000L (ppm)	(ppm_e)	Concentrate[b] 1:100 (g/70L)	B&Y Catchment[c] Tank (g/1700L)	Nutrient
Calcium Nitrate	789.4	114(N), 150(Ca)	3,094	1,342	1
Potassium Nitrate	296.3	40(N), 114(K)	2,573	503.7	
Monopotassium Phosphate	355	80(P), 102(K)	3,684	603.5	
Sequestrene 330 Fe	16.6	1.5 (Fe)	116	28.2	
Manganous Sulphate	0.77	0.25 (Mn)	5.3	1.3	
Boric Acid	5.714	1.0 (B)	40	9.7	2[d]
Copper Sulphate	0.162	0.0 (Cu)	1.1	0.28	
Ammonium Molybdate	0.092	0.05 (Mo)	0.64	0.16	
Zinc Sulphate	0.077	0.02 (Zn)	0.5	0.13	
Magnesium Sulphate	324.3	32 (Mg)	3.476	551.3	
Calcium Chloride (flake)[e]	298	50(Ca), 93(Cl)		506.6	Calcium Supplements
Calcium Carbonate[f]		100 (Ca)			

[a] From transplant into pilot plant until "golfball" fruit on first truss.

[b] The concentrate is a "top-off" solution added to the blue and yellow (B&Y) catchment tank base solution to maintain consistent ppm_e throughout the system.

[c] B&Y indicate catchment tanks for two separate feeding systems in the pilot plant.

[d] Add 150 ml. Phosphoric Acid/70L of nutrient concentration 2.

[e] If calcium chloride were used, the total conductivity of the nutrient solution would increase significantly.

[f] Calcium carbonate is used to supplement calcium (Ca). A lower salt index makes it preferable.

Table 8: Tomato Plant Formula Stage 3[a]

Salt	g/1000L (ppm)	(ppm$_e$)	Concentrate[b] 1:100 (g/70L)	B&Y Catchment[c] Tank (g/1700L)	Nutrient
Calcium Nitrate	1052.6	152 (N), 200 (Ca)	7,364	1,789.4	1
Potassium Nitrate	296.3	40 (N), 114 (K)	2,074	503.7	
Monopotassium Phosphate	526.3	118 (P), 150 (K)	3,674	894.7	
Sequestrene 330 Fe	16.6	1.5 (Fe)	116	28.2	
Manganous Sulphate	0.77	0.25 (Mn)	5.3	1.3	
Boric Acid	5.714	1.0 (B)	40	9.7	2[d]
Copper Sulphate	0.162	0.04 (Cu)	1.1	0.28	
Ammonium Molybdate	0.092	0.05 (Mo)	0.64	0.16	
Zinc Sulphate	0.077	0.02 (Zn)	0.5	0.13	
Magnesium Sulphate	324.3	32 (Mg)	3,476	551.3	
Calcium Chloride (flake)		None			Calcium Supplements
Calcium Carbonate					

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[a] From golfball fruit on first truss until first pink fruit.

[b] The concentrate is a "top-off" solution added to the B&Y catchment tank base solution to maintain consistent ppm$_e$ throughout the system.

[c] B&Y indicate catchment tanks for two separate feeding systems in the pilot plant.

[d] 150 ml. Phosphoric Acid/70L of nutrient concentration 2 was added.

Table 9: Tomato Plant Formula Stage 4[a]

Salt	g/1000L (ppm)	(ppm$_e$)	Concentrate[b] 1:100 (g/70L)	B&Y Catchment[c] Tank (g/1700L)	Nutrient
Calcium Nitrate	1052.6	152 (N), 200 (Ca)	7,364	1,789.4	1
Potassium Nitrate	296.3	40 (N), 114 (K)	2,074	503.7	
Monopotassium Phosphate	526.3	118 (P), 150 (K)	4,605	8,04.7	
Sequestrene 330 Fe	16.6	1.5 (Fe)	116	28.2	
Manganous Sulphate	0.77	0.25 (Mn)	5.2	1.3	
Boric Acid	5.714	1.0 (B)	40	9.7	2[d]
Copper Sulphate	0.162	0.04 (Cu)	1.0	0.28	
Ammonium Molybdate	0.092	0.05 (Mo)	0.64	0.16	
Zinc Sulphate	0.077	0.02 (Zn)	0.5	0.13	
Magnesium Sulphate	324.3	32 (Mg)	3,476	551.3	
Calcium Chloride (flake)		None			Calcium Supplements
Calcium Carbonate					

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[a] After first pink fruit.

[b] The concentrate is a "top-off" solution added to the B&Y catchment tank base solution to maintain consistent ppm$_e$ throughout the system.

[c] B&Y indicate catchment tanks for two separate feeding systems in the pilot plant.

[d] Phosphoric Acid/70L of nutrient concentration 2 was not added.

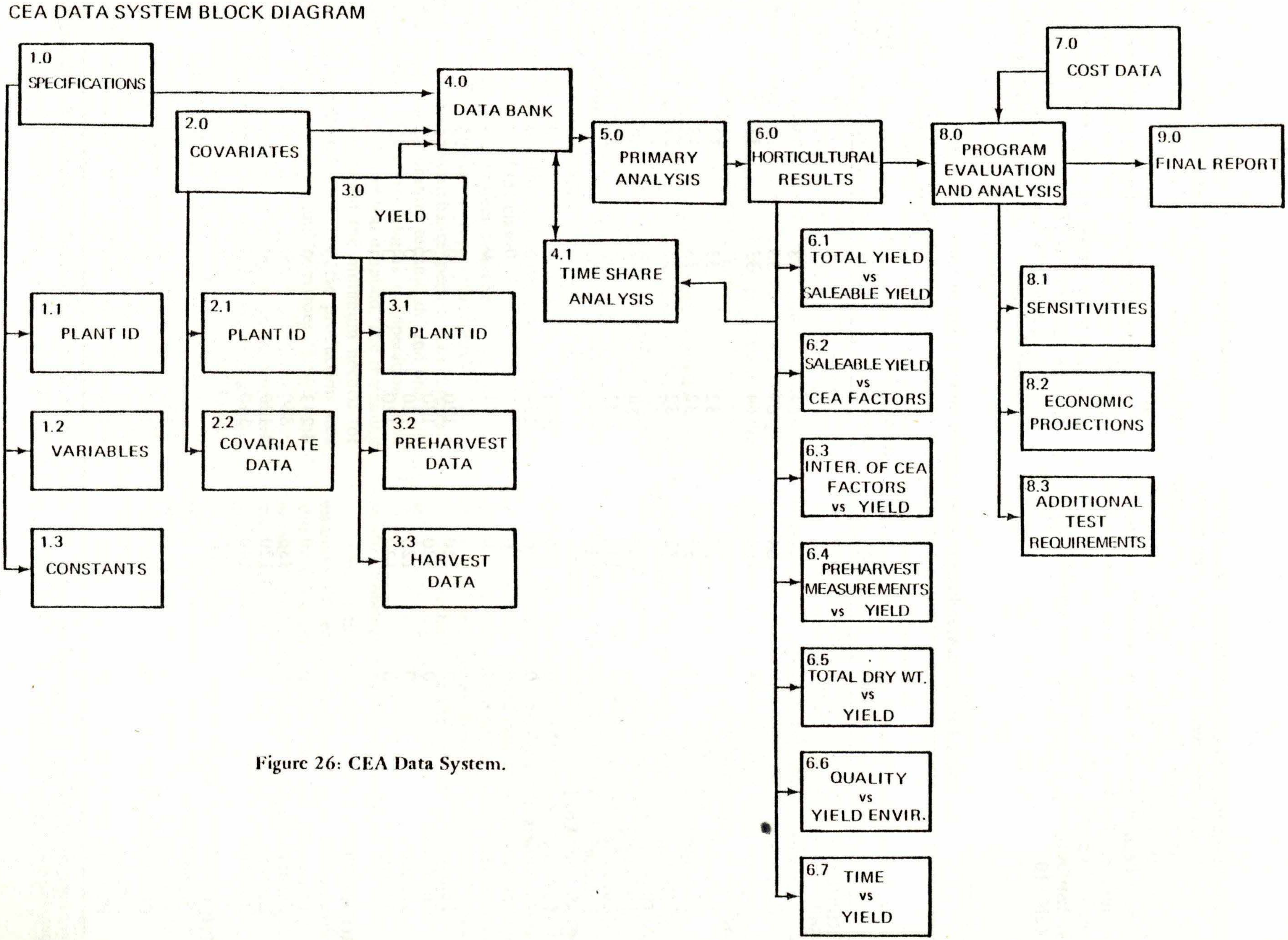

Figure 26: CEA Data System.

included all square footage not associated with production. Specifically, these were worker beds used by the CEA laborers to grow their own crops, experimental beds for new crops, and the main aisle which would not have been included in the production area in any new building. To illustrate how the costs were allocated to each crop, the area occupied and the percentage cost distribution by crop to each cost center is shown in Table 10.

Production Inputs

The inputs to production in the CEA facility at Wildwood were in three major categories: labor, energy, and materials.

Labor (Training and Employment): Production of vegetable crops within a controlled-environment facility is not a labor-intensive activity. Nevertheless, during the first two years of CEA production, a labor force of as many as nine persons was employed in the 1/4-acre production area. A justification for this large labor

Table 10: Crop Area Percent Cost Distribution by Crop to Each Cost Center

	ft^2 /Crop			% Cost Distribution to Crops		
	June	July	Remaining Months[a]	June	July	Remaining Months[a]
PERIPHERAL						
Soil						
Tomatoes	64	64	64	33	33	33
Cucumbers	64	64	64	33	33	33
Lettuce	64	64	64	33	33	33
Seed						
Tomatoes	32	32	32	33	33	33
Cucumbers	32	32	32	33	33	33
Lettuce	32	32	32	33	33	33
Nursery						
Tomatoes	384	384	384	59	59	59
Cucumbers	143	143	143	22	22	22
Lettuce	124	124	124	19	19	19
Grade-Pack-Load						
Tomatoes	0	0	768	0	0	75
Cucumbers	0	0	154	0	0	15
Lettuce	0	0	51	0	0	5
Radishes	0	0	51	0	0	5
Laboratory						
Tomatoes	0	120	120	0	25	25
Cucumbers	0	120	120	0	25	25
Lettuce	0	120	120	0	25	25
Radishes	0	120	120	0	25	25
PRODUCTION						
Production						
Tomatoes	0	0	3,243	0	0	0
Cucumbers	0	336	860	0	0	0
Lettuce	0	1,120	1,120	0	0	0
Radishes	0	140	140	0	0	0
OTHER						
Additional Space						
Tomatoes	0	0	369	0	0	25
Cucumbers	0	491	369	0	33	25
Lettuce	0	491	369	0	33	25
Radishes	0	491	369	0	33	25

[a] Remaining month figures use an average for August, September, October, and November. During June and July the facility was not operating at capacity. The figures are broken out to avoid biasing the average.

Table 11: Power Usage Per Typical Month in the Pilot Plant at Full Operation

Power Use	Unit (Kw)	Total (KwH)
Lights[a]	1.1	181,049[b]
Air Conditioning	39	56,722
Pumps	15	16,332
General	10	2,580
TOTAL		256,673

[a] Sodium is 1,114 watts per lamp, metal halide is 1,085 watts.
[b] Based on 14-hour daylength.

Table 12: Materials Requirements for Plant Growth

Peat-Vermiculite	Nutrient Film	Frequency of Replacement
Seeds	Seeds	Each crop
Planting Media	–	4 months
Soil Blocks	Soil Blocks	Each crop
Fertilizers	Fertilizers	2 months
Small Tools[a]	Small Tools[a]	1/4 per year
Plant Training[b]	Plant Training[b]	1/4 per year
Packing Materials	Packing Materials	2 months

[a] Small tools included are those needed for transplanting, pruning, clipping, general growing-area maintenance.
[b] Plant training materials include strings, clips, and wires.

force was the use of the facility for training persons within the Kenai area, specifically, but not exclusively, from KNA, for work in a CEA facility.

To accomplish this training, a 16-week course was presented by the U of A, AES at the Wildwood facility. The course consisted of two parts, horticulture and business management (Lewis, 1974b; Lewis, 1974c). Twelve persons were selected to participate in the training sessions, eight of whom were members of the KNA.

The jobs available in the CEA project at Wildwood at the end of the training course included a production manager (one position), bookkeeper, (one position), maintenance person (one position), laboratory technician (two positions), and production laborers (five positions). Persons from the training course filled these positions. Any new personnel hired after the training sessions were given on-the-job instruction by those persons who had attended the classes (Lewis, 1975b).

When the CEA Project reopened using NFT in October, 1976, the labor force was reduced to a grower-manager, a maintenance person, two production laborers, one laboratory technician, and one half-time secretary. After six months of operation, one production labor position was dropped. The remaining labor force was considered the minimum needed for reasonable operation of the 1/4-acre production area growing only cucumbers and tomatoes (Lewis and Thomas, 1975a).

Energy: Production of crops in an environment which does not depend on external climatic characteristics is energy intensive. The CEA facility at Wildwood required energy inputs for lighting in research modules and the production area: fan operation for air conditioning, air movement, and humidity control; well pump operation for water movement through air conditioning systems and for irrigation; general power use for offices, the laboratory, and the grading and packing area; and propane used in the production of CO_2. Power for lighting, fans, pumps, and general use was purchased from Homer Electric Association at commercial rates (Wick, 1974). Diesel engines were available for use as a power source if needed. Waste gases from the engines were planned to be used as a CO_2 source. However, this phase of the energy research program was not initiated (Gerlaugh, 1974). Propane for CO_2 generation was purchased from local sources. Table 11 shows the average power usage per month for the operation of the 1/4-acre pilot plant.

Materials: The materials requirements for CEA production differed little from those needed for conventional greenhouse operation. Materials required can be placed in the categories of plant growth, repair and maintenance, and general office supplies.

Materials required for plant growth varied depending on the use of pots and beds or NFT. Table 12 lists the materials requirements and the frequency of replacement. In addition to replaceable materials, small equipment was also necessary for production. Table 13 (next page) lists this equipment for each growing method and the rate of replacement (Lewis and Thomas, 1975b).

Studies Conducted to Determine Economic Feasibility

One of the objectives of the CEA Project was to establish the economic feasibility of CEA as a profitable business venture for KNA and to provide an economic blueprint for a production-sized CEA operation. To accomplish this end, various studies were conducted.

Preliminary Assessment: An assessment was made of an hypothetical 1-acre CEA facility prior to beginning operations at Wildwood. Capital investment, operating costs, and returns to investment were considered.

Break-even Analysis: Break-even analyses were conducted throughout the project at the close of each major production period during both the use of soil media and NFT. These analyses were used to monitor

Table 13: Small Equipment Required for Plant Growth

Peat-Vermiculite	Nutrient Film	Replacement Rate (yrs)
Soil Block Machine[a]		10
Soil Sterilizer		10
Irrigation System[b]		3-5
	Soil-less Culture	3-5
	Nutrient Film System[c]	5-10
CO_2 Generation	CO_2 Generation	10
Production Equipment[d]	Production Equipment[d]	3-5
Laboratory[e]	Laboratory[e]	5-10
Scales & Shrink Wrapper	Scales & Shrink Wrapper	10
Tables & Benches	Tables & Benches	10
Office Equipment	Office Equipment	10

[a] A soil block machine was purchased for manufacture of soil blocks from Alaskan peat. However, indications were that unless major structural revisions were made to existing facilities, it was more advantageous to purchase soil blocks (Lewis 1974d).

[b] Includes injectors, pipes, soaker hoses, and spaghetti tubes.

[c] Total hydroponic system including pumps and canals (Wilson 1976; Cooper 1976).

[d] Includes carts, wheelbarrows, pollinators, hand watering equipment.

[e] Optional if a good laboratory can be found for sample analysis.

costs during production periods and to indicate where greater efficiencies would reduce overall production costs. Because KNA received all buildings and land at Wildwood Village at no capital cost, the break-even analyses which were specific to the 1/4-acre pilot plant did not include capital investment. When the break-even considerations were applied to other sites or new buildings at Wildwood, the appropriate investment costs were included.

Linear Programming: A linear programming budget analysis was developed for the CEA production area (Heady and Chandler, 1958; Hilliar and Lieberman, 1967). The model was to be used to suggest alternative crop mixes and resource allocations as production continued. Data for December, 1974, through June, 1975, from the production area and the research modules were used to construct the model. Estimates were made when data were not available.

Marketing and Distribution: One objective of the marketing studies was to determine possible crop mixes for production. Salad vegetables, because of their high market value, were the first crops considered (Flynn and Thomas, 1973; Workman and Marsh, 1974). Crop mixes at various prices and various occupation levels were analyzed.

The quality of CEA vegetables was compared to that of salad vegetables available in local Alaska supermarkets by 26 households in Anchorage and 20 in Kenai participating in an 8-week program. An analysis of the questionnaires completed by the families as they assessed the flavor, texture, and general appearance of each vegetable type was carried out. Problem areas associated with marketing and distribution were also identified.

CHAPTER III

RESULTS—HORTICULTURAL RESEARCH

This chapter deals with a discussion of the horticultural research conducted both in the modules and the pilot plant. The outcome of the experiments performed are discussed in chronological order. A brief discussion of results will be given with reference to sources of original data.

MODULE RESEARCH

The majority of the research in the modules was conducted during February to December, 1975. Initially a crop mix of tomatoes, cucumbers, and lettuce was grown in the same module but this did not prove to be feasible because of differing cultural requirements and longevity (Scott, 1975). It was decided that lettuce research would be emphasized in the modules. Subsequently more than 26 "module runs"[1] of lettuce (Vinzant, 1976), 26 "runs" of tomato, and 5 "runs" of cucumber were conducted. All lettuce runs were conducted with lettuce occupying a full module, whereas this was not the case with cucumbers and tomatoes. As stated earlier, module performance (actual conditions as compared to set or nominal conditions) varied somewhat throughout the test period. A discussion of module experiments by crop follows.

Lettuce Experiments

Small-scale tests conducted in 1975 considered cultivars, soil media, soil moisture, light effects, temperature, photosynthetic effects, and NFT. The following statements briefly summarize the results obtained.

1. Peat-Perlite mix vs. Jiffy Mix.

Environment: 70°F day, 60°F night, 60% relative humidity (RH), 1500 ppm CO_2, 1500 foot candles (fc), 12-hour day, 2:1 light mix (sodium:metal halide).

Treatments: Various combinations of peat-perlite and Jiffy Mix (peat-vermiculite).

Cultivars: White Boston, Grand Rapids, Minilake.

Results: Yields and quality were low for all test conditions. This may have been due to factors in the environment other than the change in soil media or varying soil moisture. Module temperature and humidity consistently ran far in excess of the minimum acceptable conditions. Lighting proved to be suboptimal. In the test of the Jiffy Mix-perlite mixture, only Minilake was successful compared to Jiffy Mix alone.

2. Soil Moisture Test

Environment: 70°F day, 60°F night, 60% RH, 1500 ppm CO_2, 1500 fc, 12-hour day, 2:1 light mix.

Treatments: High, medium, and low moisture.

Cultivars: White Boston, Grand Rapids, Minilake.

Results: A known amount of water was applied to each pot each day: 50 ml-low, 100 ml-medium, 150 ml-high. Excessive moisture (saturation) was produced with 150 ml of water. Wilting occurred at 50 ml. For the leaf and butterhead lettuce, yield increased with increasing soil moisture. Maximum yield occurred at medium moisture for Minilake head type. Defects in quality of the product were related to cultivars. Tipburn (marginal burning of leaf edges) decreased in severity with increasing soil moisture for Grand Rapids leaf and Minilake but increased for White Boston butterhead. Tendency to bolt increased with increasing moisture for all three cultivars.

3. Nutrient Film Test

Environment: 73°F day, 73°F night, 60% RH, 2000 ppm CO_2, 1800 fc, 16-hour day, 2:1 light mix.

Cultivars: Grand Rapids, White Boston, Minilake, Parris Island Cos, Domineer.

Treatments: Plants were germinated in soil blocks and placed in tubes made of polyethylene film (TuTuff) in one trial and 4" PVC pipe with 2" slot removed and the cut piece set beneath the plants in another.

Results: Yields varied from poor to good, but quality was generally no better than for plants grown in Jiffy Mix. Serious quality defects such as tipburn, waterlogging, and bolting were just as severe in nutrient film as in Jiffy Mix. In a few cases, defects noted were worse. The polyethylene film canals were

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[1] A module run is the operation of a module through one crop cycle. This may vary in time from 35 to over 100 days depending on crop.

inferior to the PVC pipe canals because of leakage. One harvest of Grand Rapids was quite successful with an excellent total yield extrapolated to 21.6 lb/ft^2/yr with a high percentage of marketable quality. The nutrient-film experiments showed that more work was needed on moisture, light, and nutrient concentration before a successful lettuce crop could be produced.

4. **Major experiments comparing CO_2, light intensity, and photoperiod, March-December, 1975.**

Environment: See Table 14.

Cultivars: Massa, Deciminor, White Boston, Minilake, Ithaca, and Fulton.

Treatments: The tests were conducted under light wedges in which the intensity ranged from 900 to 3000 fc. Tests were conducted at 12-, 16-, 18-, and 24-hour photoperiods.

Results: These tests involved many module runs and a number of factors.

Cultivars—Grand Rapids leaf and Parris Island Cos romaine were most successful of the cultivars tested. Kwiek, Massa, Ostinata, and White Boston butterhead types were generally of poor quality with considerable waterlogging, soft rot, and tipburn. Minilake, Fulton, and Ithaca crisphead-type lettuce was likewise generally of poor quality, often failing to produce solid heads and exhibiting the quality defects stated above.

Light effects—Yields increased as total irradiance increased at all CO_2 concentrations, photoperiods, and

Table 14: Summary of Module Environmental Conditions—October 30, 1975, Runs 3-7

Module	Run	Lighting (fc)	Photoperiod (hrs)	Air Temperature (°F)				CO_2 (ppm)		Relative Humid. (%)	
		Nominal	Recorded	Nominal		Recorded		Nominal	Recorded	Nominal	Recorded
				Day	Night	Day	Night				
1	3	W[a]	12	75	65	75	66	1500	1400	60	63
	4	W	24	75	75	75	75	900	920	60	65
	5	W	12	75	65	78	68	900	870	60	69
	6	W	18	75	65	76	69	1500	1250	60	63
	7	W	12	73	63	79	70	1500	1150	60	68
2	3	W-Lu[a]	24	65	65	68	68	1500	1350	60	62
	4	1500	16	73	73	71	67	2000	1770	70	65
	4A	1500	16	73	73	73	65	2000	1840	70	70
	4B	1500	15	73	73	72	62	2000	1700	70	68
3	3	W	24	75	75	75	75	1500	1410	60	61
	4	W	24	75	75	75	75	3000	2560	60	62
	5	W	12	75	65	74	62	3000	2460	60	61
	6	W	18	75	65	76	65	3000	2600	60	62
	7	W	12	75	60	78	63	1500	1300	60	62
4	3	1000	18	75	65	75	65	1500	1390	70	69
	4	2000	16	75	65	77	65	1000	1000	70	70
5	4	2000	16	75	65	76	65	1000	950	70	70
6	3	1000	18	75	65	74	65	1500	1420	70	72
	3R	1000	18	75	65	75	64	900	880	70	70
	4	1000	16	75	65	75	66	1000	900	70	70
7	3	2000	18	75	65	74	64	1500	1370	70	69
	4	2000	18	85	85	85	77	2000	1650	85	85
8	3	W	24	65	65	65	65	1500	1440	60	64
	4	W	24	65	65	65	65	3000	2660	60	67
	5	W	12	65	55	66	57	3000	2640	60	73
	6	W	18	75	65	76	62	900	875	60	65
	7	W	18	65	55	69	58	300	2800	60	68
9	3	W	24	65	55	65	57	1500	1410	60	65
	4	W	24	65	65	64	64	900	830	60	63
	5	W	12	65	55	68	60	900	800	60	76
	6	W	12	75	60	75	58	1500	1500	60	64
	7	W-Lu	12	70	60	70	60	1500	1390	60	69

[a] Light wedge (W) consisted of a variable spacing of sodium and metal halide luminares (fixtures) which provided a variable intensity from 900-3000 fc (140-500 $\mu Em^2/sec$). Plants were distributed within the module for an intensity comparison under otherwise comparable conditions. In some cases a wedge of straight high pressure sodium illumination was used (W-Lu).

temperatures. Yields also increased as photoperiod was increased from 12 to 18 hours but there was no clear advantage at 24 hours. In terms of both yield and quality, an intensity in the range of 1500-2000 fc was best for most cultivars.

Temperature effects—Weight was inversely related to temperature, that is, the plants raised at 65° F were generally heavier than those raised at 75° F. Quality was also reduced at higher temperatures and longer photoperiods.

CO_2—Approximately 14% increase in yield was noted with incremental increases in CO_2 level from 900 to 1500 and from 1500 to 3000 ppm.

Photosynthetic efficiency—Formulas were developed (Vinzant, 1976) for the efficiency of plant growth processes as a function of the various environmental factors under test, for example, photosynthetic efficiency = weight (mg) + irradiance ($\mu E/m^2/sec$) x photoperiod (hours). Photoperiod over 12 hours did not seem to have a marked influence on efficiency. Vinzant (1976) further concludes that "efficiency does increase at high CO_2 levels with low light-intensity levels, but not at intermediate and high light-intensity levels. At 65° F day and night temperature, efficiency is increased at high CO_2 concentrations but not at lower CO_2 concentrations. Data on the efficiency of lettuce plants as a function of light quality are inconclusive. It appears that an increased need for light in the blue portion of the spectrum develops with increasing photoperiod."

Summary of Lettuce Tests: A summary prepared by Robb (1976) in September, 1975, provides a brief capsule of the growing environment for CEA lettuce.

> The best growth and quality has been achieved under the 18-hour photoperiod with approximately 1800 foot candles, 75° F day temperature and 65° F night temperature with 60% relative humidity. All three CO_2 levels (900 ppm, 1500 ppm, and 3000 ppm) showed good yields. Total yields in the best treatments were up to 16 lbs/ft^2/yr of marketable quality lettuce. The yield per acre, using these figures, would be from 100,000 pounds to 125,000 pounds for a seven-week period (from seed to harvest).

Tomato Experiments

Approximately 26 module runs of tomatoes were conducted during late 1974 and 1975. The first run was initiated according to the original experimental design discussed previously. Complete results of the first tomato run are presented in a summary prepared in early 1975 (KNA, 1975). Marketable yields of No. 1 grade fruit were low for all sets of environmental conditions. The highest yield of No. 1 grade fruit in any module was 2.2 lbs/plant (a normal greenhouse yield would be from 10-20 lbs/plant) over a 100-day period. In three of the nine modules, yields were not adequate for evaluation. Blossom end rot (BER), chlorosis, leaf distortion, and other symptoms of physiological stress related to a combination of nutritional and environmental factors were present in all of the modules.

Later module experiments with tomatoes showed similar nutritional and environmental problems in spite of intensive efforts to correct the situation. Summary statements of tomato module experiments can be made as follows:

1. A comparison of several cultivars showed that Vendor and Tropic were the two varieties exhibiting reasonable quality and yield. Tropic had best fruit size. Jetstar and Hawaiian were determined to be suboptimal.
2. The major cause of yield and quality problems in the modules was BER. Complete control of this problem was never obtained even though some environmental conditions were seemingly similar to the pilot plant where control was nearly achieved. BER may have been more prevalent in the modules than in the pilot plant because of generally higher humidity and greater saturation of the root media.

Cucumber Experiments

Cucumber, tomato, and lettuce crops, were grown in Run 1 tests in late 1974. As with the tomatoes, the cucumber results were generally less than satisfactory in all modules. Module conditions producing highest yields and quality were: 86° F day and night, 2500 ppm CO_2, 72% RH and 2000 fc; 72° F day and night, 1500 ppm CO_2, 80% RH, and 2000 fc. For tomatoes and cucumbers, these conditions produced 11.5 and 11.0 pounds per plant respectively with about 80% No. 1-grade fruit over a 45-day period. Problems such as malformed and aborted fruit were encountered. The exact causes of these conditions were not determined.

Two experiments with cucumber were carried out in the modules during 1975, both in nutrient film. In Run 4, the environment of 85° F day, 85° F night, 80% RH, 2000 fc, 2:1 light mix, 18-hour day and 1800 ppm CO_2 proved to be excessive in temperature, and RH. Nutrient concentration was also excessive in combination with this environment. Plants showed damage early and did not completely recover even though temperature, relative humdity, and nutrient concentration were reduced. Yields of up to 9.6 pounds per plant projected to a 45-day period were produced but quality was poor due to misshapen fruit.

Run 5 was terminated prematurely because of the project shutdown in late 1975. An average of only four cucumbers per plant was produced. The environment of 80°F day, 75°F night, 2500 fc, 2:1 light mix, 18-hour day, 70% RH, and 2000 ppm CO_2 proved to be much more favorable in terms of early yields and quality. The improvement in yield and quality appeared to be the result of lowered temperature, humidity, and nutrient concentrations.

A pictorial review of some of the problems encountered in tomato, lettuce and cucumber experiments is given in Figures 28 through 33 (next page).

PILOT-PLANT RESEARCH

The 1/4-acre pilot plant at the Wildwood facility was designed for commercial production. It became evident, however, as production continued, that the pilot plant could be used in a limited way for horticultural research primarily concerning various crops and cultivars, plant densities and spacings, life cycles of plants, and plant-growth techniques, thus expanding on information from the modules. The research conducted in the pilot plant continued throughout the project using both the peat-vermiculite growing media and NFT. This research was not a part of the experimental design for the research modules. However, a large part of the data obtained was used in the economic feasibility analysis for CEA. The following paragraphs will discuss, in chronological order, the results obtained from the pilot-plant research.

Table 15: Tomato Cultivar Trials, Yields, and Fruit Characteristics for a 71-Day Bearing Period, June-December, 1974

	Average Yields (lbs/ft^2)			
Cultivar	per day	total	Marketable Percentage	Characteristics of Ripened Fruit
Sunup	.018	1.25	70.40	25 lb., 8.5" circ, excellent taste
Vendor	.015	1.03	83.5	0.31 lb., 8.75" circ, excellent taste
Tropic	.022	1.54	73.4	0.38 lb., 9.0" circ, mediocre taste
Rapids Sp. Forcing	.004	0.16[a]	31.3	0.25 lb., 8.0" circ, good taste
Eurocross	.018	1.26	72.2	0.13 lb., 6.5" circ, good taste, tough skin

[a] Reflects a bearing period of 45 days. Plants could not be maintained beyond this time.

Table 16: Tomato Quality Data, June-December 1974

	Sugar (%)	Acid (%)	Vitamin C[a] (mg/100g)
Sunup	3.7	0.6	10.4
Tropic	4.8	1.0	8.9
Eurocross	4.6	0.5[b]	8.2
Vendor	5.0	2.1	18.1

[a] Vitamin C should be approximately 25 mg/100g.

[b] Eurocross, with the low acid and high sugar content was slightly bland.

Cultivar Trails using Pot Culture

June through December, 1974: During the start-up phase of the CEA pilot plant, several beds were planted in tomatoes, cucumbers, lettuce, and radishes. The pilot plant environmental parameters were: 75°F day and 65°F night temperature, 70% RH, 600-1000 ppm CO_2, 2000 fc, and a 3:1 light mix. A day length of 12 hours was used. The nutrient formula was the same as that used in the modules and shown in Table 6.

Tomatoes: The cultivars Vendor, Tropic, Sunup, Rapids Special Forcing, and Eurocross were used in variety trials. All produced a fruit weighing 3 to 5 ounces except Eurocross which produced a slightly smaller tomato, 2 to 3 ounces, preferred on the European market. The results of the cultivar trials are shown in Table 15. The trials were terminated December 30, 1974. Tropic produced the highest total yield, but the taste was mediocre and marketable percentage was low. Vendor exhibited the highest percentage of marketable fruit at 83.1%. Quality data for tomatoes are shown in Table 16.

Cucumbers: The cultivars Femdan and LaReine were the first considered for cucumber production. Fruit characteristics of the two were quite different. LaReine produced a large fruit—up to 18 inches in length and 1.5 pounds. Femdan produced smaller fruit which averaged 0.75 to 1 pound and had a length of approximately 12 inches. The results of the trials on LaReine and Femdan are shown in Table 17. LaReine showed the least waste, having a production poundage of marketable fruit of 90.4%. Femdan produced more marketable fruit in numbers of fruit because of its small size.

Lettuce: Extensive cultivar trials on lettuce were conducted. Head lettuce (Minilake) was not successful as a production crop as heads did not form. Grand Rapids, Grand Rapids Forcing, Kweik, Ostinata, and

Table 17: Cucumber Cultivar Trials, Yields and Fruit Characteristics for a 56-Day (Femdan) and 46-Day (LaReine) Bearing Period, June-December, 1974

	Average Yields (lbs/ft^2)			
Cultivars	per day	total	Marketable Percentage	Characteristics of Ripened Fruit
Femdan	.054	3.00	82.7	12" length, .75 lbs. excellent taste, crisp
LaReine	.078	3.65	90.0	16" length, 1.2 lbs. excellent taste, crisp

Figure 28: Curling in cucumbers was determined to be undesirable in packaging the product.

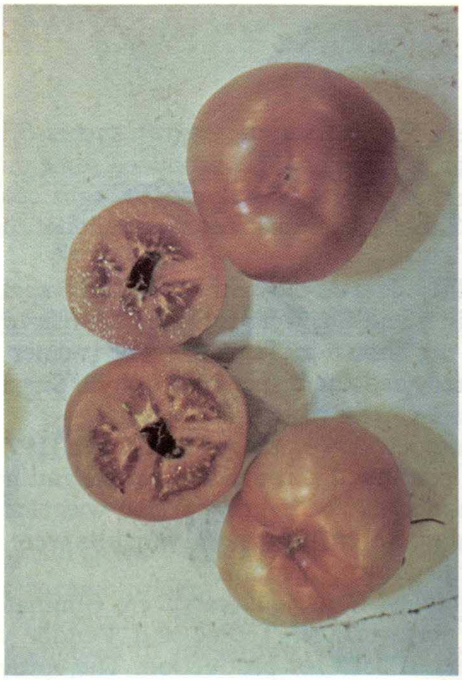

Figure 29: Internal rotting could not be detected by inspection of the whole tomato.

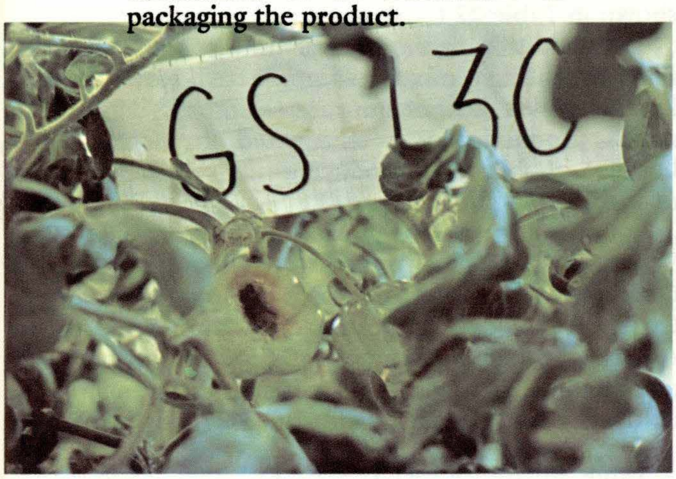

Figure 30: Blossom end rot in tomatoes was a continuous problem.

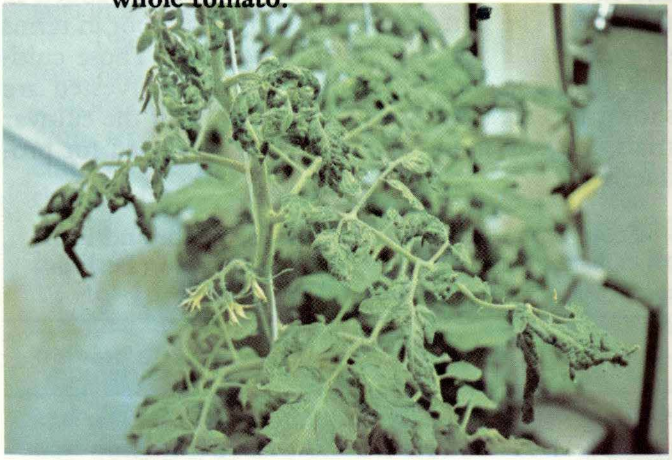

Figure 31: Tomato plants infected with virus could be detected in early stages of growth.

Figure 32: Nutrient deficiency in tomatoes was easily detectable in the leaves.

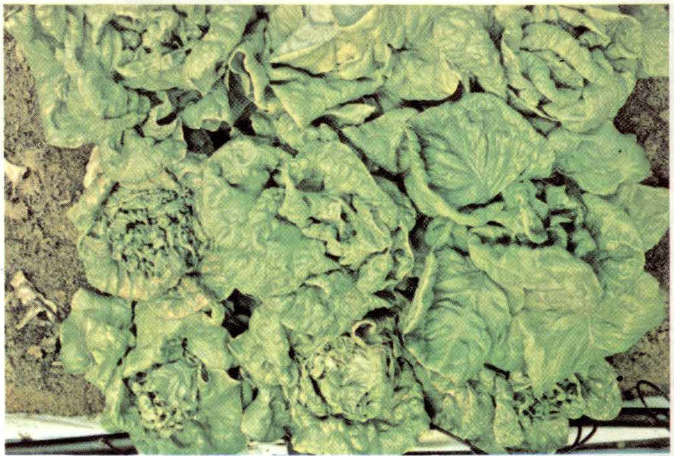

Figure 33: Lettuce tipburn was a problem in all varieties.

Massa were the leaf varieties grown successfully. Parris Island Cos, a romaine, also produced some marketable heads but in general was elongated, light colored and spindly. Table 18 summarizes the results of the lettuce trials.

Quality data on the cultivars Grand Rapids, Massa, and Parris Island Cos were recorded for marketable lettuce and are shown in Table 19. The greener romaine, as expected, had the higher chlorophyll. Sugar content and vitamin C were highest for Massa.

December, 1974, through October, 1975: Cultivar trials continued through the period and new crops were considered. The lighting period was changed to a 14-hour day. No environmental variables were changed, nor was the growing medium.

Tomatoes: Some cultivars were eliminated based on past performance. Tropic and Vendor were the main varieties used for production. The cultivars New Splendor, Farmers Wonder No. 1, Jetstar, Farmers Wonder No. 4, Tropic Greenhouse Forcing, Healani, and five experimental Hawaiian cultivars were added to the trials. The performance of most was poor in terms of marketable yield largely due to BER. Those cultivars for which a marketable yield was harvested are shown in Table 20. Based on the results of the cultivar trials, Vendor and Tropic were recommended for production.

Table 18: Lettuce Cultivar Trials, Yields and Fruit Characteristics for a 30-Day Maturation Period June-December, 1974

	Average Yields (lb.)		
Cultivar	per plant	per ft^2	Characteristics
Minilake (head type)	.50	.47	Slight defects, small heads
Parris Island Cos (romaine)	.20	.19	Slight defects, small heads
Grand Rapids	.11	.16	Slight defects, small heads
Grand Rapids Forcing	.16	.23	Good to slight defects
Kweik	.26	.37	Good to slight defects
Ostinata	.40	.57	Slight defects
Massa	.19	.27	Good to slight defects

Table 19: Lettuce Quality Data, June-December, 1974[a]

Cultivars	Sugar (%)	Chlorophyll (mg/100g)	Vitamin C (mg/100g)
Grand Rapids	2.0	.46	5.5
Massa	3.1	.38	12.0
Parris Island Cos	2.2	.76	9.0

[a] Values are comparable to field lettuce (Wooster and Blanck, 1950).

Cucumbers: In addition to Femdan and LaReine, the cultivars used for a production crop, Fembaby and Cresta were added to the trials. The resulting yields and fruit characteristics are shown in Table 21. The production from Fembaby was obtained in two harvests after which fruit were aborted. The low marketable percentage eliminated Cresta from consideration. LaReine and Femdan were recommended as production cultivars based on these results.

Lettuce: Because of the poor performance of lettuce, production was reduced to demonstration growing only. The cultivar trials were concluded in December, 1974.

Radishes: Approximately 15 cultivars of radishes were evaluated. Results were obtained for 8 cultivars of which French Breakfast, Early Scarlet Globe, and Scarlet Globe Forcing were the most successful. However, none produced a high marketable percentage due to elongated roots, premature bolting, and root-maggot problems. The results of the radish cultivar trials are shown in Table 22 (next page).

In addition to the cultivar trials, a study considering different light mixes was conducted. However, marketable yields did not improve (Hemphill, 1975). The radish production was terminated in March, 1975, because of failure to produce a reasonable percentage of marketable product.

Other Crops: Three varieties of peppers, Bell Boy, Super Set, and Yolo Wonder, were grown June through October, 1975. No effort was made to grade the fruit. Observational data indicated that, during the period August through September, 50-75% of the fruit was marketable. There was no significant difference in the cultivars. An average yield of 2.27 lbs/plant was

Table 20: Additional Tomato Cultivars, Yields for a 30-Day Period, December 1974—October, 1975[a]

	Average Yields (lbs/ft^2)		
Cultivar	per day	total	Marketable Percentage
New Splendor	.081	.243	51
Jetstar	.132	.396	62

[a] Plants were terminated after 30 days of production.

Table 21: Additional Cucumber Cultivars, Yields for a 30-Day Period, December, 1974—October, 1975[a]

	Average Yields (lbs/ft^2)		
Cultivar	per day	total	Marketable Percentage
Fembary	.237	0.71	70
Cresta	.354	1.06	41

[a] Plants were terminated after 30 days of production.

Table 22: Radish Cultivar Trials, Yields for a 30-Day Maturation Period, December, 1974—October, 1975

Cultivar	oz/radish	lbs/ft^2	Marketable Percentage
Early Scarlet Globe	.64	1.44	40
French Breakfast	1.01	2.27	55
White Icicle	1.22	2.75	no estimate
Scarlet Globe Forcing	.70	1.58	50
Stokes Scarlet Globe Forcing	.56	1.26	no estimate
Cherry Belle	.38	0.86	0
Neoro	.48	1.08	no estimate
Cavalrondo	.42	0.95	no estimate

obtained in a 4-month period. Golden Bantam sweet corn was planted and the stalks grew to 8-9 feet. The ears harvested resembled field corn in taste and texture. Three varieties of turnips, Tokyo Cross, Purple Top White Globe, and Just Right were produced. Observational data indicated the crop could be of high quality. Eggplant was also produced. High-quality fruit were harvested from the varieties Black Beauty and Blacknite. Production continued through November, 1975. For all these crops, time constraints and space limitations precluded their use as commercial crops.

Cultivar Trials using NFT

May to December, 1977: NFT crop production was begun. The pilot-plant environmental conditions were fixed at 80°F day and 62°F night, 70% RH, 600-1000 ppm CO_2, 14-hour day length, with a light intensity of 2000 foot candles and a 3:1 light mix. A standard nutrient solution was developed for the NFT system (Thornton, 1977). Outside air was added to control the day temperature.

Tomatoes: Vendor was selected as the production variety based on past experience and its high resistance to tobacco mosaic virus (TMV), outbreaks of which had occurred periodically during the use of the pot-culture technique (Thornton, 1977). Several additional varieties were considered. The first trials included Sonato and Westona and the results are shown in Table 23 (Lewis, 1977).

In June, 1977, one study of 16 tomato cultivars was conducted. The areas of concern were adaptability to NFT, incidence of TMV, fruit size and shape, percentage of BER and fruit quality. The cultivars and ratings in the areas of concern are shown in Table 24 (next page).

Cucumbers: Four varieties of cucumbers were grown in NFT during the period. These were LaReine, Toska 70, Femdan, and Farbio. The results are shown in Table 25 (next page). The cultivar LaReine was the highest producer; however, its fruit was considered large for the commercial market.

Table 23: Tomato Cultivar Trials, Yields and Fruit Characteristics for an 87-Day Bearing Period, June-December, 1977

	Average Yield (lbs/ft^2)			
Cultivar	per day	total	Marketable Percentage	Fruit Characteristics
Sonato	.097	1.65	93	Small fruit, approximately 2 oz., tart taste
Westona	.026	2.26	77	Large fruit, 5-6 oz., bland taste, tough skin

Spacing and Density Trials Using Pot Culture

It became evident during the research conducted using peat-vermiculite that tomato yields were low when compared to greenhouse yields. As an alternative to increasing yield per plant, plants were grown at closer spacings in an effort to increase yield per square foot. Spacing trials were also conducted with cucumbers in an attempt to improve yields.

December, 1974, through June, 1975: Both tomatoes and cucumbers were used in spacing studies. Spacings were not replicated within cultivars for either crop. However, each spacing study contained the same cultivar mix. The major emphasis of the studies through June was to increase the marketable yield.

Tomatoes: Plant density varied from 0.20 to 3.5 plants/ft^2 (5.0 to 2.0 ft^2/plant) at plant spacings from 12 to 16 inches. The plant density measurements included bed width and the working aisles. Pruning and training of all plants remained the same during each of the spacing trials. Table 26 (next page) shows the yields and spacings for the tomato trials. The highest yield was not obtained at the highest density. No conclusions concerning relationships of marketable yield to plant density could be made from the trial.

Cucumbers: Cucumbers were also included in spacing trials. Plant density varied from 0.28 to 0.52 plants/ft^2 or 3.6 to 1.9 ft^2/plant. Because of the small numbers of plants, it was not possible to separate pruning and training studies from the spacing studies. This affected the yields obtained and the results could not be considered conclusive. As can be seen from Table 27, the highest yields occurred at the lower plant density. No conclusions concerning relationships of marketable yield to plant density could be made.

Spacing and Density Trials Using NFT

May through December, 1977: Tomatoes: The cultivar Vendor was used in the first spacing trials. Plants were placed at 8-, 12-, 16-, and 18-inch spacings in two adjacent canals placed 18 inches on center. Pruning and training techniques were not changed for

Table 24: Tomato Cultivar Trials, June-December, 1977

Cultivar	Response to NFT	Severity of TMV	Occurrence of BER	Fruit Size and Shape	Marketable Quality
Sonato	favorable	low	minimal	1-4 oz. uniform	appearance excellent
Sweet 100	favorable	high	minimal	1 oz. uniform	cherry tomato, excellent
GS 130	very favorable	moderate	50%	4-7 oz. not uniform	large fruit, not grade 1
Westona	very favorable	moderate	50%	4-7 oz. not uniform	large fruit, not grade 1
Vendor	very favorable	moderate	20%	1-8 oz. very uniform	excellent
Jumbo	very favorable	high	20%	4-7 oz. uniform	fruit large, good as jumbo tomato
Catala	very favorable	moderate	no estimate	1-4 oz. uniform	small tomato, excellent
Vlamon	very favorable	moderate	no estimate	2-4 oz. uniform	small tomato, excellent
Lotina	favorable	high	no estimate	1-5 oz. uniform	not grade 1
Rapids Special Forcing	favorable	moderate	no estimate	2-6 oz. not uniform	rough fruit, not grade 1
Arasta	very favorable	moderate	no estimate	1-4 oz. uniform	small tomato, excellent
MM Milo	very favorable	moderate	no estimate	1-4 oz. uniform	small tomato, excellent
Fantastic	favorable	high	no estimate	1-6 oz. not uniform	not grade 1

SOURCE: KNA, 1977.

Table 25: Cucumber Cultivar Trials, Yields for a 45-Day Bearing Period. May-August, 1977

	Average Yields (lbs/ft²)		Marketable Percentage
Cultivar	per day	total	
LaReine	.039	1.76	97.4
Toska 70	.035	1.58	79.6
Femdan	.028	1.26	90.4
Farbio	.030	1.35	69.9

Table 26: Tomato-Spacing Trials, for a 70-Day Bearing Period, December, 1974—June, 1975

Plant Density		Marketable Yield (lbs/ft²)
Ft²/plant	Plants/ft²	
5.00	.20	.59
4.17	.24	.75
3.85	.26	.51
3.57	.28	.66
2.86	.35[a]	.71

[a] Spacing obtained by using two plants per 5-gallon pot.

Table 27: Cucumber-Spacing Trials, for a 45-Day Bearing Period, December, 1974—June, 1975

Plant Density		Marketable Yield (lbs/ft²)
Ft²/plant	Plants/ft²	
3.57	.28	1.46
2.94	.34	1.68
2.78	.36	0.99
2.50	.40	1.50
2.27	.44	1.49
1.92	.52	1.24

Table 28: Tomato-Spacing Trials for a 70-Day Bearing Period, May-September, 1977

Plant Density		Marketable Yield (lbs/ft²)	Marketable Percentage
Ft²/plant	Plants/ft²		
2.50	.40	2.45	98.8
3.33	.30	2.17	99.0
5.00	.20	1.96	99.4
5.88	.17	1.96	98.5

all spacing trials. The results of the spacing trials are shown in Table 28 (preceding page). Yields per square foot continued to increase as plant density increased. Marketable percentage was not adversely affected.

In October, a second crop of tomatoes was begun. The spacing trials were expanded to include new cultivars and higher densities. Each variety had a control bed of plants at 16-inch spacings and a high density bed at 8-inch spacings. Additionally, the cultivar Vendor was used in further high-density research. Control beds of Vendor at 16 and 18 inches were used. All plants in the spacing studies were topped at the eighth to tenth cluster at an approximate height of 8 feet from the canal base. During the third week of growth, the plants showed symptoms of TMV infection. There was substantial recovery, however, in approximately two months. This affected the yields recorded. However, relative comparisons can be made within the study. The results are shown in Table 29.

The increase in yield was not linearly related to the increase in numbers of plants per square foot indicating average yield per plant dropped as density increased. The cultivar which was most adapted to high density during the study was GS 130. The results of the trials indicated that high-density placement of tomatoes produced a greater yield per square foot.

Cucumbers: Spacing trials for cucumbers were conducted with the three cultivars LaReine, Femdan, and Toska 70. Only one trial was conducted and ran from May 5 to August 10. Spacings of 12, 16, and 18 inches were used with the 18-inch spacing as the control. The placement of the cucumbers in the canals was identical to the tomato placement . The results are shown in Table 30. The study indicated that LaReine and Femdan yields were higher at the lower density. The results obtained for Toska 70 seem to indicate a higher density may be possible with this cultivar to obtain a higher yield per square foot.

Table 29: Tomato-Spacing Trials, October-December, 1977

Plant Density			Marketable Yields (lbs/ft^2)[a]		Percent Increase In Yield
Plants/ft^2	Ft^2/plant	Variety	per day	total	
5.00	.20	Vendor	.0151	1.02	Control
2.50	.40		.0202	1.37	34
1.67	.60 (3 canals)		.0197	1.34	26
1.25	.80 (4 canals)		.0236	1.60	56
5.00	.20	Sonato[b]	.0149	1.09	Control
2.50	.40		.0209	1.53	40
5.00	.20	Sweet 100[c, d]	.0073	0.53	Control
3.33	.30		.0087	0.64	19
5.00	.20	GS 130	.0135	0.66	Control
2.50	.40		.0234	1.15	73
5.00	.20	Westona	.0148	0.73	Control
2.50	.40		.0198	0.97	34

[a] Bearing periods for the varieties were: Vendor, 68 days; Sonato, 73 days; Sweet 100, 73 days; GS 130, 49 days; Westona, 49 days. The difference in bearing period results from the response of the plant to topping at the 8th-10th cluster.

[b] Sonato fruit size ranges 1-4 ounces.

[c] Sweet 100 is a cherry tomato.

[d] A 12-inch spacing was used due to losses of young plants prior to transplant into the production canals.

Table 30: Cucumber-Spacing Trials for a 30-Day Bearing Period, May-August, 1977

Plant Density			Marketable Yields (lbs/ft^2)		Percent Change in Yield
Plants/ft^2	Ft^2/plant	Variety	per day	total	
5.88	.17	LaReine	.0387	1.16	Control
3.33	.30		.0300	0.90	-13
5.88	.17	Femdan	.0370	1.11	Control
5.00	.20		.0252	0.76	-22
3.33	.30		.0065	0.20	-372
5.88	.17	Toska 70[a]	.0339	1.02	Control
5.00	.20		.0393	1.18	+16

[a] Toska 70 was seeded after results of the 12-inch spacing of Femdan and LaReine were known.

Table 31: Average Total Tomato Yields and Bearing-Plant Occupancy Rates for a 120-Day Period

	Yield (lbs/ft^2)	% Plants Bearing
June-November, 1974	.52	87
December-June, 1975	.59	86

Table 32: Average Total Cucumber Yields and Bearing-Plant Occupancy Rates for a 45-Day Period

	Yield (lbs/ft^2)	% Plants Bearing
June-December, 1974	.70	65
December-June, 1975	.98	67

Life Cycles Using Pot Culture

During the initial stages of production in the pilot plant, it was evident that plant growth and development rates were more rapid than those experienced in field or greenhouse production. Although a CEA facility can be used for year-round production, tomato and cucumber plants do not necessarily produce fruit for one year or longer. Therefore, research was conducted to determine the maximum production during a plant's life cycle.

December, 1974, through June, 1975: The determination of life cycles for tomatoes and cucumbers was a major effort during the period. The parameters monitored were length of time in the nursery (seed to final transplant), days spent in the pilot plant during which no fruit was produced (nonbearing days), days during which fruit was produced (bearing days), the manner in which fruit was produced (peaks or low periods), and the relation of peaks or low production periods to plant development.

Tomatoes: Based on data obtained, it was determined that tomatoes had the following development characteristics: a nursery period of 32 days, a nonbearing period of 45 days, and a bearing period of 140 days. At the end of 140 days, production had dropped by 92% from the peak. At this point the tomatoes were terminated. By removing the plants from the pilot plant after they had been in production 120 days (bearing period), a schedule could be maintained which kept approximately 86% of the tomato production area occupied with bearing plants. Table 31 illustrates the occupancy rates and yields for June 1974 through June 1975.

Cucumbers: The development characteristics for cucumbers could only be estimated. Varying pruning and training techniques affected the characteristics of fruit bearing. During the period no representative curve could be obtained. The estimated development characteristics were a nursery period of 21 days, a nonbearing period of 22 days, and a bearing period of 45 days, after which the plants could no longer be sustained. Because of the shortness of the bearing period in relation to the nonbearing period, only a schedule which left 65% of the cucumber area occupied with bearing plants could be maintained. Table 32 shows average cucumber yields and bearing-plant occupancy rates.

July through September, 1975: Tomatoes: An effort was made to regulate weekly production based on previous period life cycles. Plants were topped when 8 to 10 clusters appeared on the plant. Under these conditions, all fruit ripened in a 70-day period. Plants were replaced on a weekly schedule. An 80% occupancy rate should have resulted. However, construction alterations in the nursery area made weekly production of a set number of seedlings difficult. Therefore, the highest occupancy rate attained was 68%. Had construction been completed, the 80% bearing rate would have been reached. Yields remained fairly stable during weeks when the bearing-plant occupancy was constant, Table 33 (next page).

Cucumbers: During July through September, an estimate was made of the cucumber life cycle. The plants began bearing after 18 days in the pilot-plant, continuing to bear for 30-days, at which time production stopped. No attempt was made to maintain a given percentage of bearing-plant occupancy because of the small number of plants. The bearing-plant occupancy and the effect on total yield is shown in Table 34 (next page).

Life Cycles Using NFT

May 5 through December, 1977: Tomatoes: The tomato life cycle did not differ from that found during July through September, 1975.

Cucumbers: Extensive work was done on cucumbers in an attempt to determine life cycles. The variety Toska 70 was used. Although various pruning and training techniques and plant densities were used, the bearing period could not be sustained longer than 30 days. Using this life cycle, a plant replacement schedule calling for removal of old plants every 5 days could be used. With this schedule 60% of the cucumber area would be occupied by bearing plants. Cucumber production was not continued after October, 1977. Therefore, this schedule could not be implemented using the NFT system.

Table 33: Weekly Yields and Bearing-Plant Occupancy for Tomatoes, July-September, 1975

	Plants Bearing (%)	Plants/ft^2	Marketable Yield (lbs/ft^2)	
			Bearing plants	All plants[a]
JULY				
Week 1	68	.28	.075	.050
Week 2	68	.28	.061	.042
Week 3	57	.30	.063	.033
Week 4	52	.30	.052	.027
Average	60	.29		
Total (month)			.251	.152
AUGUST				
Week 1	39	.32	.186	.074
Week 2	57	.32	.170	.096
Week 3	56	.30	.108	.060
Week 4	56	.30	.237	.132
Average	52	.31		
Total (month)			.701	.362
SEPTEMBER				
Week 1	57	.31	.291	.172
Week 2	64	.31	.228	.146
Week 3	63	.31	.229	.144
Week 4	62	.31	.241	.150
Average	62	.31		
Total (month)			.989	.612

[a] Includes both bearing and nonbearing plants.

Table 34: Weekly Yields and Bearing-Plant Occupancy for Cucumbers, July-September, 1975

	Plants Bearing (%)	Plants/ft^2	Marketable Yield (lbs/ft^2)	
			Bearing plants	All plants[a]
JULY				
Week 1	72	.31	.202	.147
Week 2	67	.31	.466	.312
Week 3	33	.31	.531	.178
Week 4	55	.31	.352	.195
Average	57	.31		
Total (month)			1.551	.832
AUGUST				
Week 1	33	.31	.425	.142
Week 2	89	.29	.201	.179
Week 3	76	.28	.445	.336
Week 4	78	.31	.580	.450
Average	69	.30		
Total (month)			1.651	1.107
SEPTEMBER				
Week 1	78	.31	.630	.489
Week 2	22	.31	.707	.159
Week 3	33	.31	.728	.245
Week 4	55	.31	.269	.148
Average	47	.31		
Total (month)			2.334	1.041

[a] Includes both bearing and nonbearing plants.

CHAPTER IV

RESULTS—ECONOMIC RESEARCH

The two major categories of economics research addressed during the CEA Project were costs of production of salad vegetables, using as base data the horticultural results discussed in previous chapters, and marketing and product distribution.

Break-Even Analyses in Pot Culture (Lewis and Thomas, 1974; Lewis and Thomas, 1975a, b).

Break-even analyses[1] were conducted for the major production periods through 1975. During all production periods, labor was the most significant cost item. Charges for unaccounted time made up, on the average, 35% of total labor available (Table 35). The labor structure was designed such that each worker carried out a specific task but did not participate in the production process from seed to finished product. Labor-time studies were conducted during the first production period. The most significant aspect of the labor-time studies was that little improvement occurred in performance over time. In those tasks which required initiative and some independence, labor became more efficient. However, in those tasks which were repetitive and required only rote performance, times remained the same or increased slightly (Table 36, next page). Assembly-line production has traditionally been a problem to management. Data of the type presented are not unusual at start-up or after a process has continued for lengthy periods.

Table 35: Pilot-Plant Labor Time in Man Months[a]

	June	July	Aug.	Sept.	Oct.	Nov.
Total Available Time	4.4	4.4	5.9	8.9	8.9	8.9
Measured Task Time	1.0	1.5	3.9	5.4	5.6	5.5
Idle Time[b]	.9	.9	.9	.9	.9	.9
Unaccounted Time	2.5	2.0	1.1	2.6	2.4	2.5

[a] Based on a 165-hour month.
[b] Includes lunches and coffee breaks.

Suggestions on improvements concentrated particularly on modification of the labor organization structure. The basic recommendation was to formulate a manufacturing plan using as a basis the cost-center approach developed. Concentration would be on labor specialization, but using the "modular" or "group of related task" approach (Horngren, 1972).

Tomatoes and cucumbers were the only crops marketed commercially. Yields and costs were tabulated and gains or losses calculated. Table 37 shows the results for December, 1974, through June, 1975. The pilot plant operated at a loss. In an effort to provide guidelines for greater efficiency in the following production phase, a hypothetical analysis was conducted to show how the break-even point could be reached.

Table 37: Yields, Costs, Market Prices, and Returns June, 1975

	Yields (lbs/ft^2)	Costs ($/ft^2)	Market Price ($/lb)	Returns ($/ft^2)
Tomatoes	.40	$2.20	$.70	($1.92)
Cucumbers	.98	$2.19	$.40	($1.80)

Cost Reduction: Labor utilization studies indicated that a work force of four persons including a working manager, a maintenance person, a nursery person, and a production laborer could complete all tasks in the pilot plant. Although module studies had not been conducted at the 1000-fc intensity level, there were some indications that this intensity could provide equal results of 2000-fc, thus reducing electrical costs. Mechanical flushing of the air-conditioning system was adequate and could be used in place of the chemical-water treatment to reduce material costs. The costs calculated using these reduced inputs of labor, electricity, and materials are shown in Table 38 (page 32).

Increases in price per pound and/or yield per ft^2 were considered using the reduced costs calculated for both tomatoes and cucumbers. The results of these

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[1] All break-even analyses conducted considered only operating costs.

Table 36: Labor-Task Times (Per-unit Basis)

	Timed Unit	August	October	Frequency
Soil Preparation:				
Prepare and sterilize	15 ft^3 = 2940 blocks	.082 min/block 4 hours down time	.082 min/block 4 hours down time	once weekly
Prepare soil blocks	2 ft^3 = 392 blocks	.036 min/block	.024 min/block	once weekly
Germination:				
Seed, water, label sticks	8 trays—448 blocks	.045 min/block	.045 min/block	once weekly
Germinate and transport	8 trays—448 blocks	.045 min/block	.029 min/block	lettuce as required
Nursery:				
Data collection	16,000 soil blocks	.0004 min/block	.0004 min/block	daily
Hand fertilize and water	16,000 soil blocks	.006 min/block	.006 min/block	daily
Rogueing	16,000 soil blocks	.002 min/block	.002 min/block	2x weekly[a]
Transplant to 4" pots	25 pots	2.5 min/block	3 min/block	as required
Cleaning	16,000 soil blocks	.004 min/block	.004 min/block	2x weekly[a]
Pilot Plant:				
Tomatoes:				
Transplant to 12" pots	64 four-inch pots	2 min/plant	2 min/plant	as required
Pollinate	200 plants	.25 min/plant	.15 min/plant	daily
Prune, train, rogue	200 plants	.10 min/plant	.5 min/plant	daily
Fertilize and water (Automatic and hand)	all plants	.14 min/plant	.004 min/plant	daily
Harvest	200 plants	.29 min/plant	.29 min/plant	3x weekly
Cucumbers:				
Transplant to 12" pots	64 four-inch pots	2 min/plant	2 min/plant	as required
Prune, drain, rogue	100 plants	.48 min/plant	.48 min/plant	daily
Fertilize and water (Automatic and hand)	100 plants	.08 min/plant	.034 min/plant	daily
Harvest	100 plants	.29 min/plant	.29 min/plant	3x weekly
Lettuce:				
Prepare bed before planting	1 bed—800 plants	.35 min/plant	.27 min/plant	once weekly
Transplant	1 bed—800 plants	.72 min/plant	.39 min/plant	once weekly
Fertilize and water	1 bed—800 plants	.01 min/plant	.01 min/plant	daily
Harvest	1 bed—800 plants	.45 min/plant	.90 min/plant	3x weekly
Radishes:				
Seed	42 seeds—1 ft^2	No Data Available	1.2 min/bunch	as required
Mix fertilizer	2 gal.—4'x4' plot		.03 min/bunch	at planting
Hand fertilize	4'x4' plot—67 bunches		.03 min/bunch	3x weekly
Water by hose	4'x4' plot—67 bunches		.03 min/bunch	3x weekly
Harvest	42 plants		.48 min/bunch	as required
Grade, Pack, Load:				
Tomatoes	20 boxes (approximately)	No Data Available	1.25 min/lb.	3x weekly
Cucumbers	20 boxes (approximately)		.625 min/lb.	3x weekly
Lettuce	20 boxes		.19 min/lb.	3x weekly
Radishes	42 plants		3.6 min/bunch	as required
General:				
Soil analysis	11,000 ft^2	.01 min/ft^2		daily
Data (in pilot plant)	11,000 ft^2	.13 min/ft^2		daily
Record keeping	11,000 ft^2	.26 min/ft^2		daily

[a] As required, but of the approximate frequency indicated.

Table 38: Incurred and Reduced Production Costs—June, 1975

	Tomatoes		Cucumbers	
	Incurred[a] (\$/ft^2)	Reduced (\$/ft^2)	Incurred[a] (\$/ft^2)	Reduced (\$/ft^2)
Labor	\$ .88	\$.30	\$ .87	\$.28
Electrical	.71	.31	.71	.31
Materials	.54	.24	.54	.24
Propane	.03	.03	.03	.03
Laboratory Fee	.04	.04	.04	.04
TOTAL	\$2.20	\$.92	\$2.19	\$.90

[a] Costs incurred are those recorded for the pilot plant. Labor costs include a charge for staff of \$.47 per square foot.

Table 39: Increases in Market Price and/or Yield Necessary to Reach the Break-Even Point—June, 1975

	Present Yield (lbs/ft^2/mo)	Present Price (\$/lb)	Increased Yield (lbs/ft^2/mo)	Increased Price (\$/lb)
Tomatoes	.40	–	–	\$2.30
	–	\$.70	1.31	–
Cucumbers	.98	–	–	\$ .92
	–	\$.40	2.25	–
	–	\$.65[a]	–	–

[a] Price which could be obtained in the Anchorage market. Yield would have to increase to 1.38 lbs/ft^2/mo. to cover cost of this price.

calculations are shown in Table 39. A price over \$.70 per pound wholesale for tomatoes would have been difficult to obtain given 1975 Anchorage market trends. However, the higher price of \$.65 per pound for cucumbers was in line with 1975 Anchorage wholesale cucumber prices. This indicated that cucumber production was able to provide sufficient revenue to cover costs of production in the CEA pilot plant if an adequate marketing effort was undertaken.

As a result of the break-even considerations, recommendations were made to improve the production operation. Strongly emphasized was the need for an overall management plan which would include methods of labor utilization, production-flow estimates, labor scheduling, quality control of product, standard operating procedures, and marketing planning.

Break-Even Analysis for NFT (Lewis, 1977; Lewis and Thomas, 1977).

There were two major production periods. The first was the commercial production of a cucumber crop from May through June, 1977; the second, a tomato crop from August through December, 1977.

Cucumber costs of production for May through June, 1977, were estimated. Salaries included a grower-manager, a laboratory technician, a maintenance person, a half-time secretary and 2.5 production laborers. These costs were not appreciably different from those estimated as reduced costs in 1975 and were: salaries \$.74/ft^2, utilities \$.46/ft^2, and materials \$.08/ft^2, for a total of \$1.28/ft^2.

Yields from four varieties of cucumbers grown at three different spacings were tabulated. It was possible to extend the bearing portion of the life cycle of some cucumber varieties to 50 days. However, after 30 days, production of grade 1 fruit decreased while grade 2 and waste production increased. It was found that the cultivar LaReine at an 18-inch spacing was highest in the production of marketable fruit and was lowest of the high-production varieties in waste production. However, the large fruit presented a marketing problem. The smaller fruit of Toska 70 at 16-inch spacings was better suited to the market and produced a marketable yield of 1.18 lbs/ft^2/month for bearing plants and .71 lbs/ft^2/month for all plants.

The European cucumber brought a retail price of \$1.00 per pound in the Anchorage market in 1977. Therefore, a wholesale price of \$.70 per pound would not be unrealistic. During the winter months, this could rise to \$1.00 per pound. However, with average yields of .71 lbs/ft^2/month, a market price of \$1.80 per pound would have to be realized to reach the break-even point.

A tomato crop was grown in a fourth of the pilot plant from August through December, 1977. Costs of production were tabulated and were found to be: Salaries \$.78/ft^2, utilities \$.46/ft^2, and materials \$.08/ft^2, for a total of \$1.32. As with the cucumbers, the costs were not appreciably different from those estimated as reduced costs in 1975.

An attempt was made, using 8-inch spacings with the cultivar Vendor to maintain a production level of 6,000 to 7,000 lb/mo (.55 to .64 lbs/ft^2/mo.) to assess commercial feasibility. At the same time, pruning and training techniques were changed to a minimum pruning system with plant topping at the 8-10 cluster level to determine if labor costs could be reduced below \$.78/ft^2/month. A 1,000 ft^2 area was used for this purpose. Labor costs were reduced by approximately 1/3, bringing production costs to \$1.06/ft^2/ week or an equivalent .72 lbs/ft^2/month with 80% of the plants bearing. The break-even point could have been reached at an average market price of \$1.47 per pound. The results of this commercial test were somewhat inconclusive because of TMV throughout the production area. This reduced yields on the Vendor cultivar at 8-inch spacings by approximately 20% from the May through June, 1977, period. All other varieties were similarly affected.

Linear Programming (Budget Analysis)

A linear programming framework was developed for the CEA pilot plant using data obtained through June, 1975. This modeling method could be used to suggest alternative crop and resource allocation once a feasible solution was obtained.

The technical data necessary for construction of the linear programming model were developed from studies in the pilot plant and modules and from horticultural "best guesses." Even so, because of data limitations, the only environmental variable that was considered at several levels was carbon dioxide (CO_2). The levels considered were: 750, 1200, and 2000 ppm.

The following fixed environmental conditions were assumed in the model: temperature, 75°F day, 65°F night; photoperiod, 13 hours; light intensity, 2000 fc; humidity, 70%, light mix, 3:1. Yield, crop mix, labor, electricity, propane, and material costs from 1975 were also incorporated.

The solution indicated that no combination of inputs of CEA production levels determined through June, 1975, made the pilot plant economically feasible in a commercial operation mode, although the 2000 ppm CO_2 level did provide the lowest break-even price. The major reason for this lack of feasibility was the small size of the plant. Assuming no change in plant size, the linear programming analysis was modified to determine what changes were necessary to make the solution feasible (Table 40). With all inputs except labor held constant the 1/4-acre facility still was not commercially viable unless a premium price were obtained for the products.

Marketing and Distribution

A market assessment for fresh vegetables in Anchorage was conducted in 1973 (Flynn and Thomas, 1973). The report concluded that predicted population growth in the Anchorage area suggested a market which will expand to a size much larger than that which already existed. Tomatoes were the favorite salad-vegetable crop and a fresh, high-quality tomato would have significant market acceptance.

A quantitative examination of the Anchorage-Kenai market area was published in May, 1974 (Workman and Marsh, 1974). Over 2,600,000 pounds of tomatoes and 600,000 pounds of cucumbers were marketed in this area in 1973, Table 41 (next page). These figures do reflect the growth of the Alaskan economy and population since the construction of the oil pipeline.

A consumer study was conducted in late 1975 to investigate consumer preferences for CEA vegetables (Workman, Lewis, and Marsh, 1977). Tomatoes, cucumbers, lettuce, and radishes purchased at a supermarket in the Anchorage area were compared by selected households to CEA produce. CEA vegetables were typically assigned higher values than the produce purchased in local supermarkets on all characteristics tested although, for most comparisons, the differences were slight. The major difference was the superior appearance of CEA radishes. The study also showed that Anchorage consumers rated both CEA and imported vegetables higher than did Kenai consumers. A pictorial review of the crops produced in the CEA facility is given in Figures 34 through 39 (page 35).

Table 40: Feasible Solution (Break-Even) for 1/4-Acre Production Area Using a Linear-Programming Model ($)

	CO_2 Level (ppm)		
	750	1,000	2,000
Tomatoes[a]			
Gross Revenue @ $.60/lb.	1.81	2.40	2.64
Total Costs (full labor)[b]	9.81	10.20	10.39
Total Costs (½ labor)[c]	7.68	7.90	8.05
Break-even price ($/lb.)			
Full labor	3.27	2.55	2.36
Half labor	2.56	1.98	1.83
Cucumbers[a]			
Gross Revenue @ $.37/lb.	.93	1.24	1.37
Total Costs (full labor)[b]	5.07	5.10	5.17
Total Costs (½ labor)[c]	3.92	3.95	4.02
Break-even price ($/lb.)			
Full labor	2.02	1.52	1.40
Half labor	1.56	1.18	1.09
Lettuce[a]			
Gross Revenue @ $.40/lb.	.21	.28	.32
Total Costs (full labor)[b]	1.77	1.78	1.79
Total Costs (½ labor)[c]	1.33	1.34	1.35
Break-even price ($/lb.)			
Full labor	3.37	2.54	2.24
Half labor	2.53	1.91	1.69

[a] Tomato, cucumber, and lettuce analyses considered the crop occupying the full ¼ acre.

[b] Full labor implies a work force of 9 persons: a grower-manager, bookkeeper, maintenance person, laboratory technician and helper, 3 production workers.

[c] One-half labor implies a work force of 4.5 persons: a grower-manager, .5 bookkeeper, maintenance person, .5 laboratory technician and 1.5 production workers.

SOURCE: Lewis, C. E., and W. C. Thomas. 1975a. CEA economics report No. 3, Paper No. 3, Inst. of Agric. Sci., Univ. Ak., Fairbanks.

Table 41: Quantities of Salad Vegetables by Weight Sold in the Anchorage/Kenai Market, May, 1974 (lbs)

Month	Head Lettuce	Leaf Lettuce[a]	Tomatoes	Radishes	Cucumbers	Green Onions
	Per Week					
January	102,866	3,575	40,536	3,967	10,000	5,692
February	123,863	3,054	43,859	4,365	8,713	6,245
March	98,693	3,720	43,800	4,180	7,284	5,780
April	122,902	5,207	58,740	4,802	9,477	6,347
May	87,842	5,227	68,682	5,535	12,761	6,746
June	101,847	5,351	58,433	6,668	13,058	7,144
July	85,265	3,956	57,041	6,752	15,830	7,739
August	90,736	3,282	43,359	6,377	15,557	6,946
September	72,408	3,265	46,442	6,248	15,000	7,172
October	87,474	2,882	49,482	4,434	13,784	5,689
November	83,009	3,349	43,679	4,456	12,965	5,653
December	89,243	3,003	44,568	4,325	10,966	5,843
Weighted Average	95,298	3,825	49,919	5,179	12,138	6,416
Annual Total	4,944,490	198,892	2,595,800	269,303	631,200	333,654

[a] This column includes Romaine, Red leaf, and Bibb lettuce.

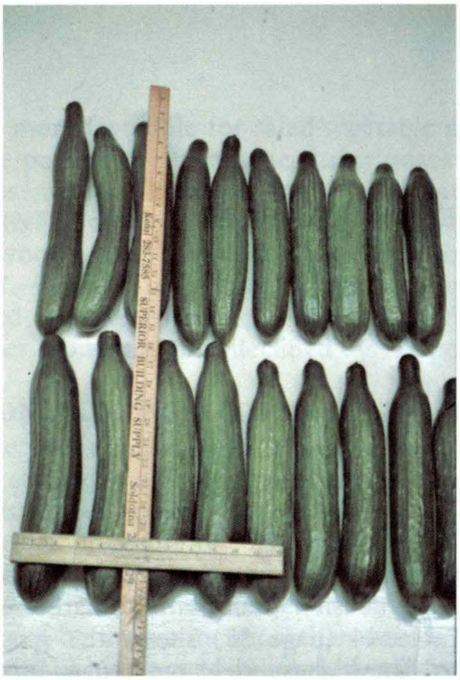

Figure 34: European cucumbers varied in size but were consistent in quality.

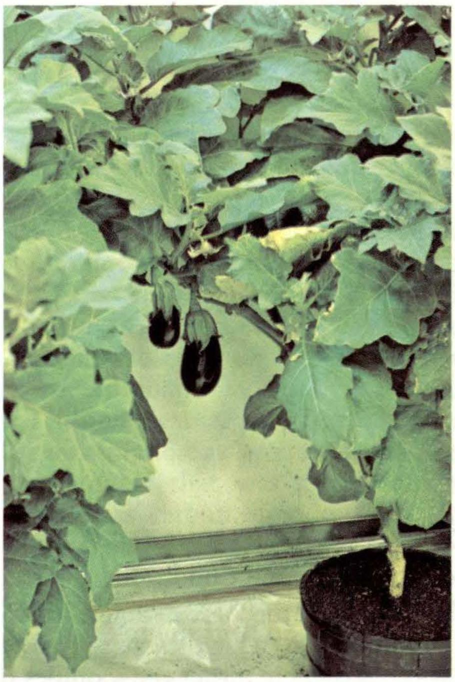

Figure 35: Eggplant was quite successful although not grown as a production crop.

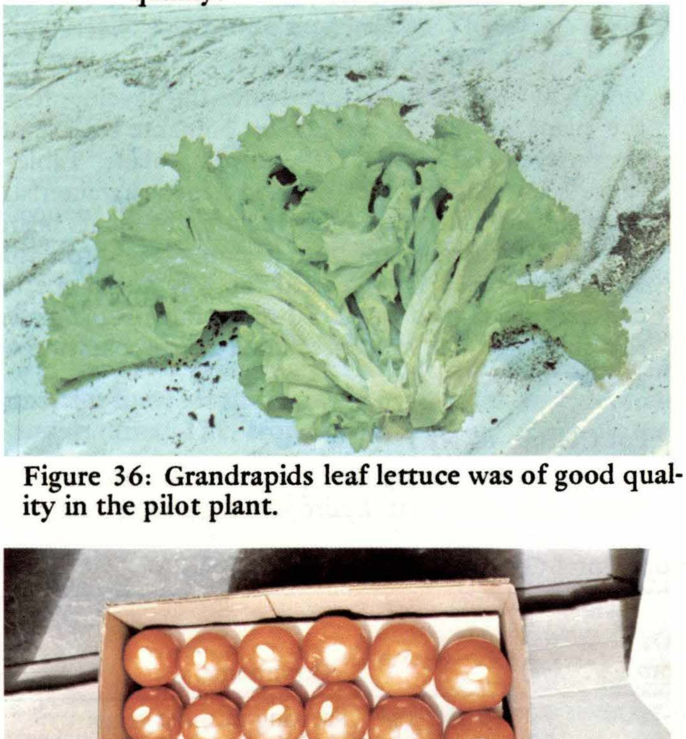

Figure 36: Grandrapids leaf lettuce was of good quality in the pilot plant.

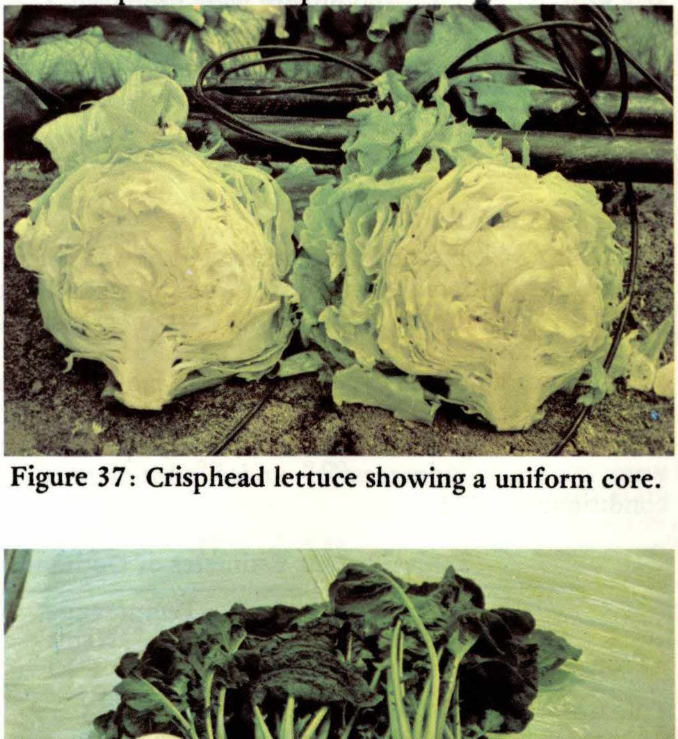

Figure 37: Crisphead lettuce showing a uniform core.

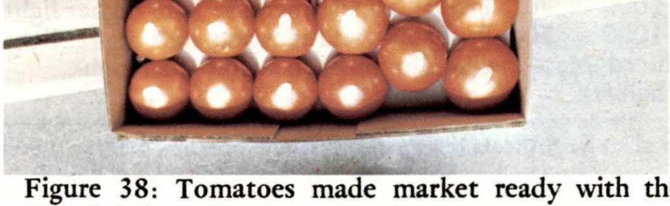

Figure 38: Tomatoes made market ready with the KNA label.

Figure 39: Turnips were of high quality.

CHAPTER V

CONCLUSIONS, IMPLICATIONS, AND RECOMMENDATIONS

CONCLUSIONS—HORTICULTURAL RESEARCH

Optimum Environmental Conditions

Table 42 gives the best estimate of the environmental conditions in which greatest marketable production was obtained in either the modules or the pilot plant. In some cases, the crop was grown only in the pilot plant where environmental parameters were fixed. If a satisfactory yield and quality were produced, these conditions were suggested as a basis for future study. In other words, a satisfactory crop can be grown. By fine-tuning the environment (change conditions slightly), yields and quality may be improved or costs of inputs reduced.

Crops and Cultivars

A list of crops and cultivars which showed a combination of desirable traits for CEA are shown in Table 43 (page 37). It was learned that certain crops and varieties required special conditions. For example, head lettuce and Bibb-type lettuce were more difficult to produce than leaf types. Peppers needed careful control of nitrogen level to avoid flower drop. Radishes were generally unsuccessful under pilot-plant CEA conditions in 1975.

Plant Density

Optimum space utilization was considered by conducting density trials with tomatoes and cucumbers. Table 44 (page 37) shows the spacings which produced the highest yield per square foot under the pilot-plant environmental conditions for those varieties showing traits desirable in CEA.

Plant Cycling

The best time to renew a crop (replace old plants with new) can be determined once the development of the plant is known. Schedules of plant replacement were developed in the 1/4-acre pilot plant. Table 45 (page 37) shows the development characteristics, replacement schedule, and percentage of plants bearing with these schedules for both cucumbers and tomatoes. Little difference among cultivars was noted. Lettuce cultivars developed in 25-30 days, but problems with the quality of the crop precluded the preparation of a production schedule.

Pot Culture vs. NFT

Research during 1975 in the modules at Wildwood indicated that hydroponic growing techniques

Table 42: Best Estimates of Optimum Environmental Conditions for CEA Cropping

Crop	Light[a] Intensity (fc)	(hrs)	Temperature Day (°F)	Night (°F)	CO_2 (ppm)	RH (%)	Comments
Tomato	2000-2500	14-16	75	65	600-1000	70	BER, TMV limiting in most trials
Cucumber	2000-2500	18	86	86	2500	72	Curling and abortion of fruit was limiting
Lettuce	1200-1800	12-16	75	55-65	1000-1500	60	Tipburn, chlorosis limiting in most trials
Pepper[b]	2000	14	75	65	600-1000	70	Excess N can cause blossom drop
Turnip[b]	2000	14	75	65	600-1000	70	Probable yield increase with higher light
Eggplant[b]	2000	14	75	65	600-1000	70	Probable yield increase with higher light
Radish	Insufficient data, few marketable radishes produced. Metal halide illumination better than high-pressure sodium (HPS) or mix HPS-MH (metal halide).						

[a] Intensities at various leaf levels in tomato and cucumber varied with plant height from less than 100 fc to more than 4000 fc. Levels stated are at 6-inches above the base of the plant.

[b] Crops grown only in the pilot plant under a single set of environmental conditions and are included for information only.

may be more favorable for salad-vegetable production than the pot culture techniques using peat-vermiculite mixes as media. Therefore, in 1976, a nutrient film system (NFT) developed by Alan Cooper, was installed at Wildwood. After completion of production research in 1977, it was shown that tomato production had improved by approximately 1/2 pound/ft^2 while cucumber production had declined by 1/5 pound/ft^2.

CONCLUSIONS—ECONOMIC RESEARCH

The crops considered for production in the CEA facility at Wildwood were those which would bring a high return per square foot of space utilized (either high market price and/or high volume yield). Because of the high energy requirements, one obvious crop which would satisfy this objective is a flower crop. However, a better justification than aesthetic pleasure for the use of high-priced and/or low-supply fuel is the production of a high-quality food product. Specifically, in areas with harsh climatic conditions, high-quality salad vegetables are virtually unavailable and do play an important role in the human diet. Therefore, the decision was made to use the CEA facility at Wildwood for research in the growing of such salad vegetable crops as tomatoes, cucumbers, lettuce, and radishes.

After research had been in progress for six months (June through November, 1974), it became evident that tomatoes and cucumbers could be produced for the commercial market. Lettuce and radishes, however, were not of a quality adequate for the commerical market.

A major aspect of the cost-of-production studies was the break-even analysis. Table 46 (page 38) summarizes these results showing production cost, revenue, and returns. The crops considered are tomatoes and cucumbers. Although marketable yields were obtained for lettuce and radishes, the percentage never exceeded 50% of total yield.

Table 43: Cultivars Best Adapted to CEA

Crop	Cultivar	Characteristics
Tomato	Vendor	TMV tolerance, uniform shape, size, consistent production.
	Sonato	Good yield and fruit quality, TMV, and BER tolerant.
	GS 130	Large fruit, high yield, tolerates close spacing, some tolerance to TMV, BER.
Cucumber	Toska 70	High yield, excellent quality, uniform.
	LaReine	Large fruited, high yield, excellent quality.
Lettuce	Grand Rapids	Leaf type, short season (25 days), tolerant to tipburn, large leaves.
	Parris Island	Romaine type, good quality, tolerant to tipburn.
Radish	French Breakfast	Best yield and quality.

As shown in Table 46, both incurred and budgeted cost resulted in negative returns. Incurred cost did not decrease to the budgeted cost level implying that, to reach a break-even point, increases in yield and/or market price shown in Table 47 (page 38) would have to occur.

The determination of an economic optimum depends on biological information and input and output price information at several levels. The only environmental variable that was successfully analyzed at several levels was carbon dioxide (CO_2). In the linear programming model used, three levels of CO_2, 750,

Table 44: Densities Producing the Highest Yields Per Square Foot in CEA

Cultivar	Density (plants/ft^2)	(ft²/plant)	Yield (lbs/ft^2/mo.)	Comments
		Tomato		
Vendor	.40	2.50	1.06 lbs.	Plants grown in 2 NFT canals at 8 in. spacing.
Sonato	.40	2.50	.63 lbs.	Plants were affected by TMV, 2 NFT canals were used with plants at 8 in. spacing.
GS 130	.40	2.50	.71 lbs.	Plants were affected by TMV, 2 NFT canals were used with plants at 8 in. spacing.
		Cucumber		
Toska 70	.20	5.00	1.18 lbs.	Plants grown in 2 NFT canals at 16 in. spacing.
LaReine	.17	5.88	1.17 lbs.	Plants grown in 2 NFT canals at 18 in. spacing.

Table 45: Tomato and Cucumber Replacement Schedules[a]

Crop	Development Characteristics	Replacement Schedule	Percent Bearing per Unit Area
Tomato	Nursery 32 days Nonbearing 45 days Bearing 70 days	Every 7 days	80
Cucumber	Nursery 21 days Nonbearing 22 days Bearing 30 days	Every 7 days	60

[a] Replacement schedules are based on horticultural information only.

Table 46: Cost of Production and Revenue Per Month for Tomatoes and Cucumbers

Period	Incurred Cost[a,b] (\$/ft^2)	Reduced Cost[a] (\$/ft^2)	Market Price (\$/lb)	Marketable Yield (lbs/ft^2)	Returns to Incurred Cost (\$/ft^2)	Returns to Reduced Cost (\$/ft^2)
June, 1975						
Tomatoes	2.20	.92	.70	.40 lbs.	(\$1.92)[e]	(\$.64)
Cucumbers	2.19	.90	.40	.98 lbs.	(\$1.80)	(\$.51)
August, 1977						
Tomatoes	1.32[c]	.92	.70	.85 lbs.[d]	(\$ .73)	(\$.33)
Cucumbers	1.28	.90	.65	.71 lbs.	(\$ .82)	(\$.44)

[a] Incurred cost refers to the actual expenditures in the pilot plant. Reduced costs were derived from budget estimates for increased efficiency in labor, electricity and materials.

[b] Includes wage increase to employees.

[c] By improving efficiency in cultivation techniques on plants at high density, incurred costs were reduced to \$1.06/ft^2 /month which would result in a return of (\$.47).

[d] Yields are projected from high density plants effected with TMV assuming non-TMV infected plants would produce 20% higher marketable yield than the effected plants (Chapter IV).

[e] ( ) indicates loss.

Table 47: Increases in Yield or Market Price Necessary to Reach Break-Even at Reduced Costs

	Yield (lbs/ft^2 /month)		Price (\$/lb)	
	Attainted	Increased	Attained	Increased
Tomatoes	–	1.31	\$.70	–
Cucumbers	–	1.38	\$.65	–
Tomatoes	.85	–	–	\$1.08
Cucumbers	.98	–	–	\$ .92

1200 and 2000 ppm, were considered. The results indicated that for tomatoes, cucumbers, and lettuce, the higher CO_2 levels were associated with higher production. However, the additional economic advantage for the change between 1200 ppm and 2000 ppm was insignificant. In conclusion, considering only the CO_2 level and holding the remaining environmental variables and prices constant, the CO_2 level in Table 42 approaches the economic optimum. The remaining environmental estimates in Table 42 are probably in the feasible region of economic production but their relationship to economic optimum is uncertain.

PROBLEMS ENCOUNTERED

There are substantial differences in crop production between greenhouse facilities and a CEA environment. Difficulties encountered in technological and horticultural areas for CEA production substantiate this conclusion. Ideally module experiments should have provided numerous set points for all test crops which could then have been subjected to economic analysis to give maximum yield per dollar of cost.

Multiple problems limited the achievement of production and quality goals that met even good greenhouse yields and quality, much less the potential of CEA stated in the initial proposal and in promotional literature available (KNA, 1973; GE, 1976). These problems were both technological and horticultural. Technological problems caused lack of confidence in module results. Horticultural problems were perhaps the overriding cause of failure to achieve good data from the modules. Insufficient knowledge existed on the interaction between light, temperature, CO_2, and humidity and nutrient needs. The assumption that plant nutrition could remain at a constant high level without its inclusion as a variable in the experimental design was faulty.

Problems of BER in tomato, tipburn in lettuce, and, possibly, abortion in cucumber may all have had a common cause: the inability of calcium to be taken up and transported to fruits and new leaves. This condition has received considerable research attention (Olson, Tibbitts, and Struckmeyer, 1967; Robbins, 1937; Stout, 1934; Tibbitts and Rao, 1968). A number of environmental factors are implicated such as excess water in the root area, excess salts, especially potassium and magnesium, excess humidity, lack of air circulation (reduced transpiration), and, in a few cases, lack of calcium in the root medium. These problems were not solved adequately in the Wildwood CEA facility soon enough. This resulted in poor data for all crops at various periods of the project.

In spite of the many technological and horticultural problems, the module experiments did produce a significant amount of data for future research and commercial development. The CEA project at Wildwood was the first instance in the world in which nine large growth chambers were used in a methodical study of horticultural plant growth with the goal of an economic appraisal of each environmental factor.

IMPLICATIONS

Risk

It is appropriate to place in perspective the risk associated with investment in a commercial CEA facility. Risk will not be assessed in quantitative terms, but by delineation of those factors which determine success or failure of a project.

Management: CEA requires substantial management control over both the production and marketing phases. The prospect of business failure is enhanced by incomplete organizational development, inadequate marketing, or poor personnel management. Any future CEA project will have reduced risks of early failure by development of a sound planning effort.

Labor: Management must depend on reliable labor to make a highly technical project a success as an investment. CEA requires a well-trained staff of personnel to perform precise functions at just the proper time. Compensation should be viewed as fair and working conditions adequate in order to provide incentive to employees to perform to these job specifications and remain on the job. High employee turnover increases the chance of inadequate performance of critical operations which could impede crop production.

Energy: The major risk factors concerning energy are availability of a source and price. In recent years, with increased world concern over sources of energy, a technology dependent on large energy inputs is somewhat at a disadvantage. This assumes that greater value placed on particular energy sources such as fossil fuels is represented by higher prices. Therefore, unless the consumer of a CEA crop is prepared to pay a substantial price for the produce, cheap energy sources are necessary to make CEA economically viable.

Energy sources may include geothermal, solar, or, in special cases, fossil fuels (such as natural gas which, for transportation or other reasons, is not economically viable without a local use). Any potential investor must consider, even if a cheap energy source is available at time of project planning, how long that source can be expected to remain inexpensive. Stated in other terms: Will the payout from the investment be rapid enough to overcome the risk of substantially higher energy costs anticipated in the near future?

Facility Design and Equipment: CEA is a unique approach to the commercial production of plants. It requires special types of buildings and equipment. Difficulties may arise and risk increase if an attempt is made to utilize inadequate facilities for a CEA production plant. A good example is the Wildwood location. The engineering and mechanical repair requirement associated with the facility was substantial just in keeping the conglomeration of old and new equipment functioning. These problems were not fully foreseen in the planning stages of the project.

Other Production Inputs: CEA depends on the use of technology more than any other commercial plant-production system. This inherent condition adds to the risk associated with commercial CEA . CEA at Wildwood pointed to numerous occurrences where only limited information was available on environmental conditions and plant response. It is evident that additional applied research is necessary to refine the CEA production system. The question is: When has enough research been done? The answer depends on the risk the investor wishes to take.

Disease: Control of disease and insects is necessary in commercial development of CEA. A standard operating procedure must be developed to control access to the production areas and restrict activities such as smoking by plant employees. Financial risk is greatly affected by quality and quantity of produce from the plant.

Potential Uses of CEA

CEA-type projects are possible in several situations. Very timely applications might be in poor agronomic areas such as the arctic or desert regions where agricultural production would not otherwise be possible. These areas are usually characterized by poor transportation systems but do have population pockets where vegetables are included in the diet. Highly populated urban centers could also be the location of CEA production plants. In general, in areas where transportation or produce is difficult or expensive and/or where energy is abundant and relatively inexpensive, CEA production becomes more economically feasible.

In Alaska, where there are regions of the state in which surface land and water transportation are either unreliable or nonexistent, the possibility of CEA production's being economically viable are enhanced. However, a note of caution should be given. If transportation difficulties exist for perishable salad vegetables, they may also exist for required inputs into the CEA production process.

The energy issue is also critical. Even in a remote Alaskan location, if a cheap and abundant energy source is not available, CEA production is possible only if the consumer of the produce is prepared to pay a substantial price for the commodity. The high energy requirements of CEA relative to any other type of commercial plant-growing system must be a major consideration in the planning of a CEA facility.

Using an admittedly superficial data base, the following two examples appear possible for CEA production. Submarines can remain away from port for indefinite periods of time. If they are nuclear powered, the energy source is abundant. The added energy cost for on-board CEA production would be insignificant. The crew members would have access to fresh vegetables and flowers to add to the quality of life aboard ship. The second example is man's ventures into outer space. In this case, the energy probably could be solar generated, which means abundant fuel at costs no different than if CEA did not exist aboard the spacecraft. Again, quality-of-life products would be produced in a situation where technical problems or transportation costs might preclude obtaining salad vegetables and associated crops from the earth.

RECOMMENDATIONS

Further Research

The problems encountered in the Wildwood project which occurred in spite of input from highly experienced engineers, mechanics, plant physiologists, horticulturists, and economists testify to the fact that further research is needed before success in a commercial CEA venture is assured. Listed below are some of the plant-related areas deserving intensive study:

1. **New crops.** A thorough horticultural and economic analysis of potential crops of all kinds is needed. While this project emphasized food crops, other crops with higher potential value per unit area should be investigated. These might include the whole range of ornamental crops including roses, pot chrysanthemums, Easter lilies, flowering bulbs, bedding plants, and house plants. In addition, specialty crops grown for drug or medicinal use might be profitable. Drug plants requiring security would be well adapted to a location such as Wildwood.
2. **New crop varieties**: The several cultivars of each crop responded nonuniformly to the environmental parameters studied. Not all responses were as expected nor were they favorable for commercial production. This indicates that further research should be conducted on the development of cultivars specifically for use in CEA facilities.
3. **Lighting.** The use of year-round, continuous lighting is the major difference between greenhouse and CEA crop production. Not only light quantity but light quality affects plant growth. During the CEA experiments at Wildwood, quantity of light available was varied by varying day length and power output. Research on light quality was limited and inconclusive. Because the spectrum of light both in the visible and nonvisible range will effect plant growth, further research in this area should be conducted.
4. **Nutritional factors.** This aspect needs particular emphasis in future CEA research. Insufficient effort was spent during the Wildwood CEA project on the analysis of several levels of nutrients on plant growth. Had this area been given adequate emphasis from the beginning of the project, greater achievement of several objectives could have been possible. In spite of the extensive growth-chamber research there is a great deal yet to be learned about the interaction of nutrition and other environmental factors before commercial adoption of this technique is possible.
5. **Crop management.** Space utilization and plant management within a CEA facility must be organized in such a manner that plant care is minimized while yields per ft^2 are maximized. Research efforts were begun in the Wildwood facility in an attempt to reach this goal. Plants were placed at various densities to determine if yields per ft^2 could be increased. Plant life cycles were studied. This effort was directed toward maintaining as high a percentage of plants as possible in the bearing stage. Various cultural techniques were integrated into the density and cycling studies. These different techniques were shown to affect labor cost and yields. Because of time constraints, the results of each of these studies cannot be considered conclusive. It is important to continue this research effort for the crops produced at Wildwood as well as for any other crops which may be considered for future CEA production.
6. **Energy.** With high energy consumption, is generally associated waste energy. CEA production is no exception. Table 48 shows the sources of waste energy associated with CEA production and lists possible applications. Calculations have not been made to determine the economic impact of the various uses of waste energy. However, it would seem obvious that research in energy-saving methods would prove advantageous.
7. **Technology.** Indications are that if labor use in any operation is to be minimized, trade-offs to advanced technology must be considered. A listing of areas where advanced technology may be a trade-off to labor or other production inputs is given in Table 49 (next page).

Table 48: Waste-Energy Sources and Alternate Applications

Source	Application
Exhaust from diesel generators	CO_2 for plant growth. Heat for greenhouses. Heat for general office and/or storage areas.
Heat from growth lamps	Vent out of building into greenhouses rather than air condition for cooling. Recirculate hot air over cooling pads to use in cooling the growing area. Hot-water heat for soil warming for field crops if run through a collector tank. Heat for general office and/or storage areas.

Table 49: Applications of Advanced Technology

Category	Trade-Off to:	Comments
Lighting	Energy Use	Movement of lights from ½ production area where they have remained for 12 hours to remaining area.
Trolley systems	Labor	Installed in harvesting, packing, and loading areas.
Washing, packaging grading	Labor	Automated systems for all market-preparation activities.
Nutrient system	Labor Fertilizers	Automated sampling and replenishment of nutrient solution.
Plant movement	Labor Seedlings	Trolley movement of plant from nursery into growth areas requiring little handling and less seedling loss.

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