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ECONOMIC ANALYSIS OF SYSTEMS USED TO ESTABLISH CA ATMOSPHERES

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Introduction

Currently, several methods of atmosphere establishment are being used in New York. New methods and equipment are being introduced and accepted but at the same time, many old "oxygen burners" are still in use. Growers and storage operators have questioned the benefits of the new technology and its economic merits. In an attempt to answer some of these questions, a storage operator survey was conducted in the spring of 1985. This is a report and analysis of the results of that survey.

Atmosphere Establishment

The survey data indicate the following methods of CA establishment are currently being used in New York:

1. Room flushing with an open flame generator (Wilde Type).
2. Room flushing with a catalytic burner (Tectrol Type).
3. Recirculating room atmosphere through a catalytic burner (COB Unit).
4. Recirculating room atmosphere through a catalytic ammonia cracking burner (Holec Generator).
5. Flushing room with liquid nitrogen (liquid Dewar and home-made vaporizer).

Principle of Operation

All of the oxygen burning generators (methods 1, 2, and 3) were fueled with propane. The flushing type burner arrangement is shown in

Millions of membrane tubes make up the fiber bundle in each module of the GENERON* air separation system. The fiber bundle is strategically constructed to facilitate the flow of gases around and through the individual hollow fibers. Oxygen (and water vapor) flow through the membrane walls into the hollow fibers and exits at the ends of the module. Dry enriched nitrogen exits via an outlet on the side of the module.

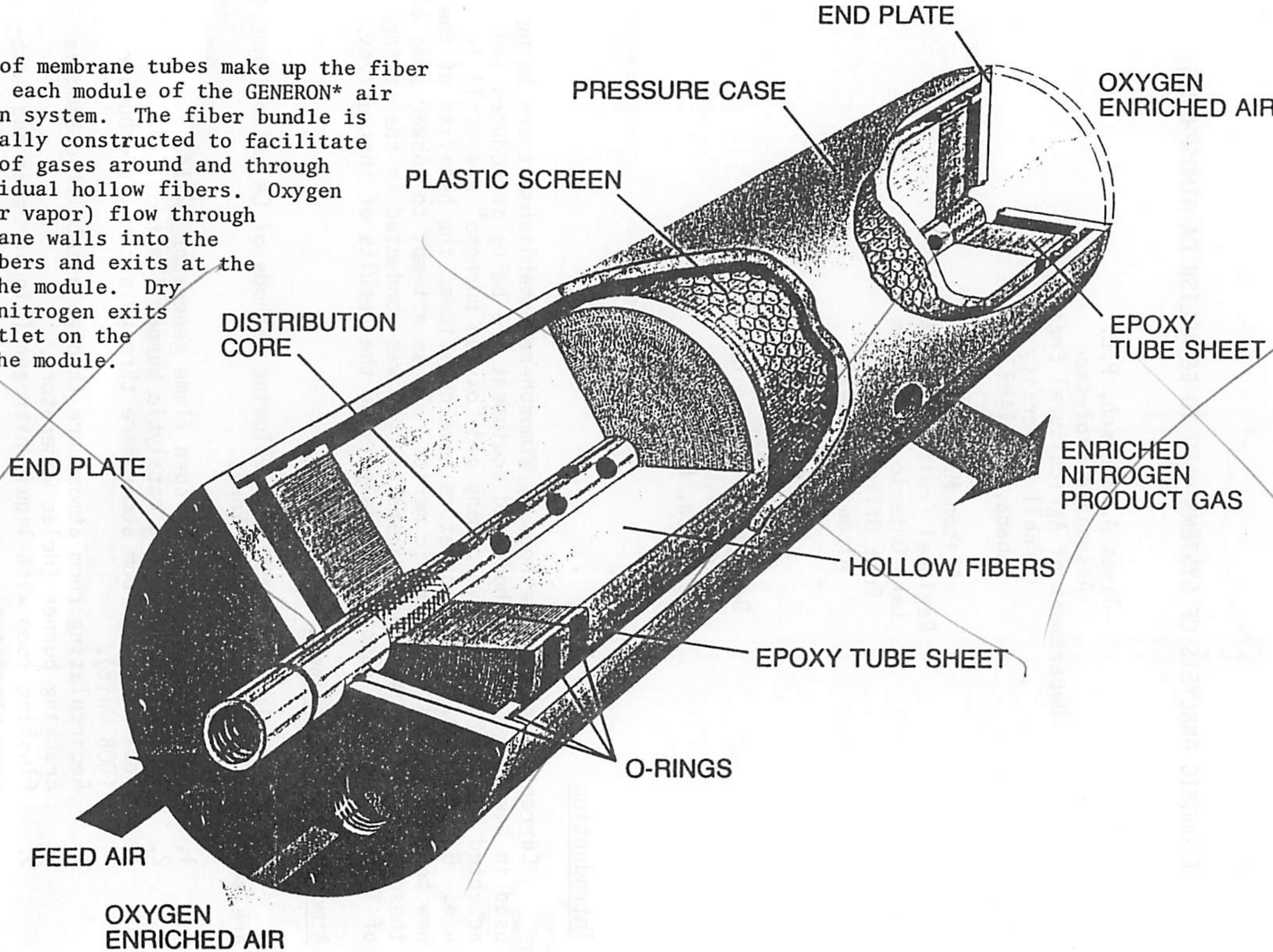


Figure 1a. These units combine propane and air in a combustion chamber (Wilde) or in a catalyst bed (Tectrol) and pump the cooled combustion products into the room. The theoretical combustion reaction for propane and air (methods 1 and 2) is given below:

$$C_3H_8 + 5O_2 + 20N_2 \quad 3CO_2 + 20N_2 + 4H_2O \qquad (1)$$

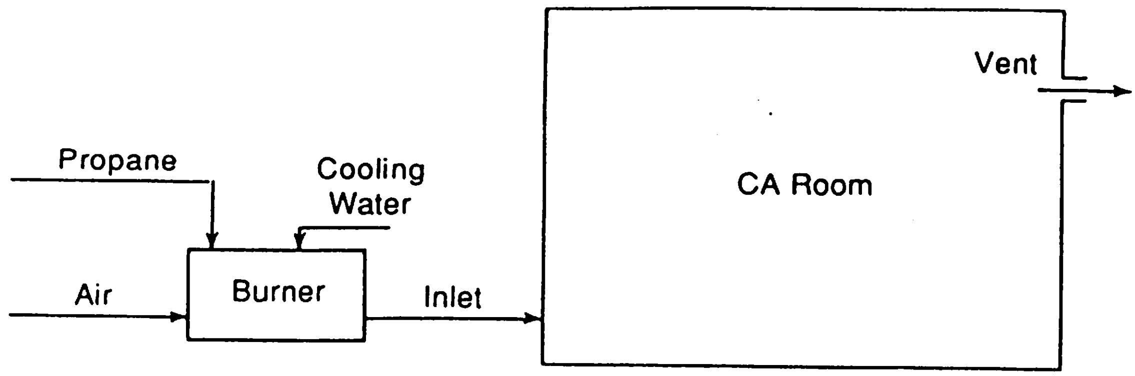
Stoichiometrically each pound of propane consumes 231 cubic feet of air to produce 190 cubic feet of nitrogen, 24.4 cubic feet of CO_2 and 1.64 pounds of water vapor. Excess water vapor is condensed in the exhaust cooler.

The rate of oxygen depletion in the CA room depends upon the flushing rate and volume of voids in the room. The void space was calculated from the survey data and bulk density of the fruit (5) to be 1650 cubic feet per 1000 bushels stored.

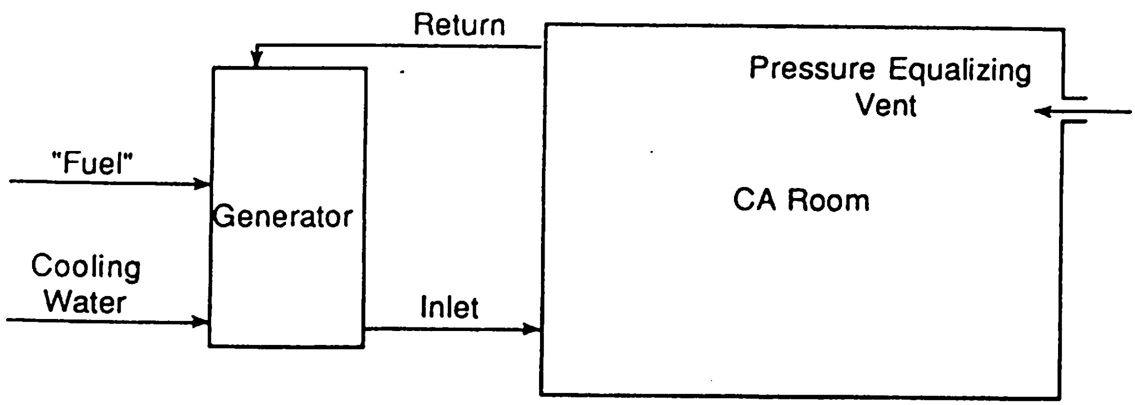
The oxygen concentration is related to the number of exchanges of the void volume as shown in Figure 2. This relationship is valid for both flushing and recirculating type generators. Note that each volumetric exchange removes half of the oxygen in the room. The first exchange results in a decrease in concentration from 21% to 10.5%; the second from 10.5% to 5.2%; and the third from 5.2% to 2.6%. All of our analyses are based on the establishment of a 5.2% oxygen level from initial concentration of 21%. This requires two volumetric exchanges or 3,300 cubic feet of atmosphere per 1000 bushels of apples in storage.

The corresponding CO_2 level for propane generated atmospheres is also shown in Figure 2. Excess CO_2 must be removed from the room because it is toxic to the fruit. If the CO_2 is held at 5% approximately 15 cubic feet of CO_2 must be removed for each pound of propane burned. We did not obtain sufficient CO_2 scrubbing data to include this analysis in our report. Previous reports (3, 4) indicate that 20-100 pounds of hydrated high calcium lime per 1000 bushel would be needed to remove the scrubber generated CO_2. The cost of this additional lime would be part of the CA generating cost.

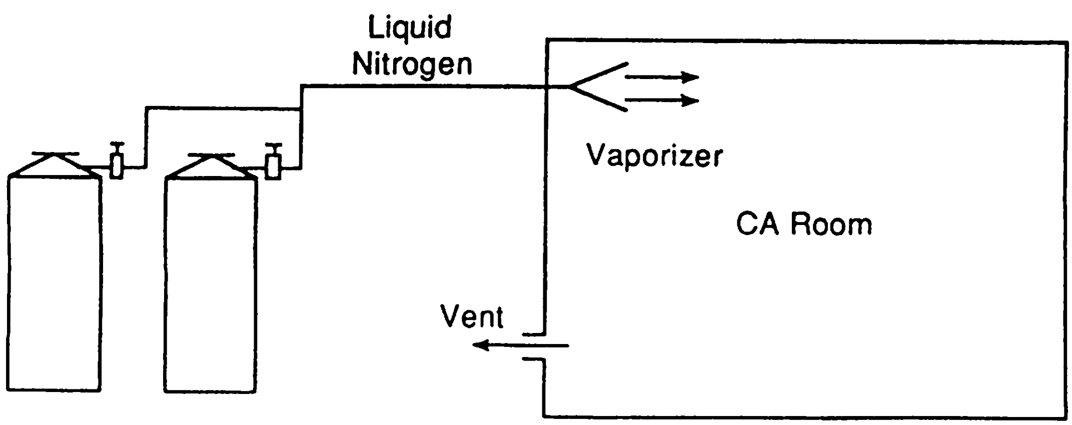
The recirculating catalytic burner arrangement is shown in Figure 1b. The combustion process requires the same propane to oxygen ratio shown in equation 1, although the oxygen to nitrogen ratio decreases as the oxygen is consumed. During recirculation, each pound of propane combines with 41 cubic feet of oxygen to produce 24.4 cubic feet of CO_2 plus 1.64 pounds of water vapor. Since the volume of CO_2 exhausted is less than the volume of oxygen taken in, the CA room is vented to permit air to enter and equalize the pressure. The oxygen in the entering air stream (3.3 cubic feet per pound of propane used) is consumed in the catalytic oxygen burner. If the CO_2 is held at 5% by scrubbing, approximately 280 cubic feet of CO_2 must be absorbed for each 1000 bushels of



a. Flushing with exhaust from "burner"



b. Recirculating atmosphere through CA generator (generator in catalytic burner or ammonia cracking type)



c. Flushing with liquid nitrogen

Figure 1. Operating Characteristics of Atmosphere Generating Systems

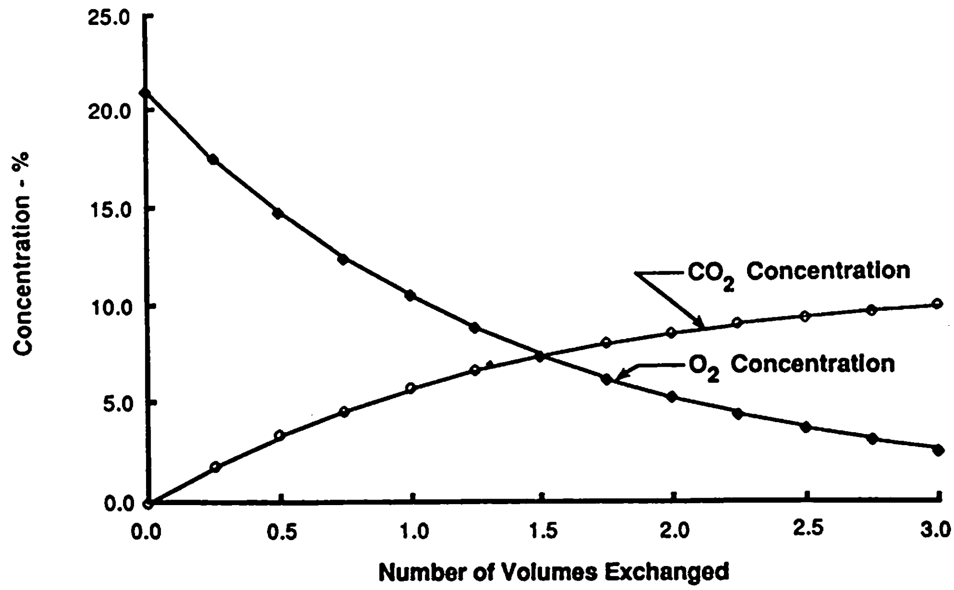


Figure 2. Oxygen and Carbon Dioxide Concentration as a Function of Volumetric Exchange

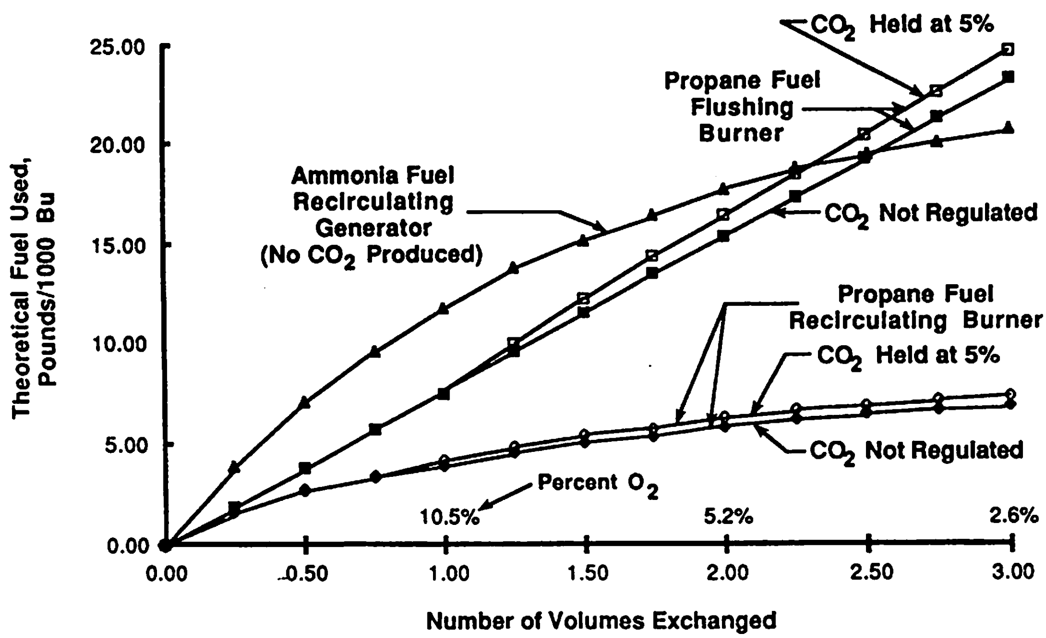


Figure 3. Theoretical Fuel Use by CA Generators

storage. This volume of CO_2 is replaced by an equivalent volume of air during the atmosphere generation period.

The recirculating ammonia fueled generator operates in the manner shown in Figure 1b. The chemical reaction in the ammonia fueled generator occurs in a cracking and combustion process as follows:

$$\text{Cracking} \quad 4NH_3 \quad 2N_2 + 6H_2 \tag{2}$$

$$\text{Burning} \quad 2N_2 + 6H_2 + 3O_2 \quad 2N_2 + 6H_2O \tag{3}$$

One pound of anhydrous ammonia consumes 15.8 cubic feet of oxygen and returns 10.5 cubic feet of nitrogen. Air replaces the 5.3 cubic feet of lost volume and this adds 1.1 cubic feet of oxygen for each pound of ammonia used.

Liquid nitrogen is introduced via a copper tube manifold as shown in Figure 1c. The liquid boils at -320°F (-196°C) and is vaporized in a copper distribution header located at the refrigeration evaporator intake or discharge. One liter of liquid vaporizes to 21.5 cubic feet of nitrogen gas. A remote sensor (thermocouple) is located near the fruit in the top bin to monitor the temperature. The liquid input rate is adjusted manually to prevent freezing of the fruit in the room.

Theoretical Fuel Use

The theoretical fuel use for each generator is shown in Figure 3. Fuel use is based upon the chemical reaction (Equations 1-3) presented above and includes the additional fuel necessary to convert the oxygen entering the room when recirculating generators are used. Fuel use is based upon a voids volume of 1650 cubic feet per 1000 bushels of fruit and is presented as a function of the number of volumes exchanged. The oxygen concentration corresponding to the number of exchanged volumes is also given. The upper curve for the propane fueled generators (both flushing and recirculating) represents the fuel requirements when CO_2 is maintained at a 5% concentration. The CO_2 level reaches 5% at .75 and 1.0 exchange volumes for the recirculating and flushing burners respectively. No CO_2 is introduced by the ammonia fueled generator.

Economic Analysis

The cost analysis of each atmosphere generating system was based on the following economic factors:

1. Depreciation at 6.67% per year (15 year life expectancy of equipment).
2. Annual interest charge of 10% of average value.

3. Repair cost of 2% of new cost per year plus catalyst replacement each 3000 hours for COB and Tectrol. (Catalyst cost: COB 1 $785, COB 3 $900, COB 6 $1000, Tectrol $900)
4. Fuel and energy costs:
   a. Propane at 20.8 cents per pound.
   b. Anhydrous Ammonia at 25.0 cents per pound.
   c. Electricity at 10 cents per kWh.
5. Water at $2.50 for 1000 gallons.
6. Cost of CO_2 scrubbing not included. (Tectrol operated as atmosphere generator only)
7. Maximum atmosphere generating period of 40 days (960 hours).

The total annual operating cost includes the annual fixed costs, the utilities cost (fuel, electricity, and water) and the annual cost of catalyst maintenance. The annual catalyst cost was treated as a variable cost because our survey data indicated catalyst life expectancy varied a great deal among operations. Several operators had experienced premature catalyst failures due to freon poisoning from refrigerant leaks or from freon diffusion into CA rooms from freon "frothed" urethane foam insulation. Technically the catalyst cost could be treated as an annual fixed cost but it is identified as a separate item here to indicate its contribution to the total operating cost. We have purposely itemized the contribution of each economic factor to permit direct item by item comparison between systems. This itemization makes it possible for the reader to substitute alternative cost values if desired and to determine the effect these values have on the final cost.

Purchase price and annual fixed cost data are summarized in Table 1 for the generator systems included in the survey. The annual fixed cost includes 6.67% depreciation, 10% interest on the average value of the generator over its total life (1/2 of new cost) and 2% repair cost for a total of 13.67% of the purchase price.

The variable operating costs for utilities are given in Table 2. These costs are based on the hours of operation needed to reduce the oxygen level from 21% to 5% for 1000 bushels of fruit. The unit fuel, energy and water costs were standardized at the rates mentioned previously.

The total annual operating cost budget for the various generators is developed in Table 3. The relative contribution of each identifiable cost factor is shown. No life expectancy data was available for the Holec-50 catalyst so no cost is identified for this item in Table 3. We did not obtain sufficient data to include CO_2 scrubbing cost for the burners shown in Table 3. If hydrated lime, costing $7.00 for 100 pounds, were used at the rates suggested in (3) an additional annual cost $1.37 per 1000 bushels would be added to the propane fueled generator operating costs. If the recommendation of 100 pounds lime per 1000 bushel (4) were followed, the added cost of CO_2 removal would be $7.00 for 1000 bushels stored.

Table 1. Purchase Price and Annual Fixed Cost for CA Generators Included in Survey.

Generator	Tectrol	Wilde	COB-1	COB-3	COB-6	Holec-50
Number in Survey	4	2	3	4	2	1
New Cost, $	18,800	4,000	10,700	14,000	16,000	33,700
Annual Fixed Cost, $(a)	2,576	548	1,466	1,918	2,192	4,617

(a)Includes depreciation, interest, and repair costs

Table 2. Operating Time, Utilities Use, and Utilities Cost From Survey Data

Generator	Tectrol	Wilde	COB-1	COB-3	COB-6	Holec-50
Operating Time, hr/1000 bu(a)	3.6	1.5	4.0	2.5	1.0	2.1
Fuel Consumption, lb/hr	5.5(b)	7.5(b)	3.0(b)	4.8(b)	7.0(b)	18.9(c)
Electrical Demand, kW	0.425	0.33	7.5	10.0	34.5	20.0
Water Use, gal/hr	330	300	300	450	510	100
Utilities Cost, $/1000 bu	7.22	3.52	8.50	7.80	6.17	9.45

(a)Time Required to reduce O_2 from 21 percent to 5 percent per 1000 Bu
(b)Propane fuel
(c)Anhydrous ammonia fuel

Table 3. Annual Operating Cost for Generators in Relation to Bushels of CA Storage

Bushels	Generator	Tectrol	Wilde	COB-1	COB-3	COB-6	Holec-50
50,000	Fixed Cost	2576	548	1466	1918	2192	4617
	Utilities	361	176	425	390	308	472
	Catalyst Replacement(a)	0(b)	NA	53	0(b)	0(b)	0(c)
	Annual Total Cost, $	2937	724	1944	2308	2500	5090
	Cost $/1000 Bu	58.70	14.50	38.90	46.20	50.00	101.80
100,000	Fixed Cost	2576	548	1466	1918	2192	4617
	Utilities	722	352	850	780	617	945
	Catalyst Replacement(a)	108	NA	106	75	0(b)	0(c)
	Annual Total Cost, $	3406	900	2422	2773	2809	5562
	Cost $/1000 Bu	34.06	9.00	24.22	27.7	228.09	55.62
200,000	Fixed Cost	2576	548	1466	1918	2192	4617
	Utilities	1444	704	1700	1560	1234	1890
	Catalyst Replacement(a)	217	NA	212	150	67	0(c)
	Annual Total Cost, $	4237	1252	3378	3628	3493	6507
	Cost $/1000 bu	21.18	62.60	16.89	18.14	17.46	32.53
400,000	Fixed Cost	(d)	548	(d)	(d)	2192	4617
	Utilities	(d)	1408	(d)	(d)	2468	3780
	Catalyst Replacement(a)	(d)	NA	(d)	(d)	134	0(c)
	Annual Total Cost, $	(d)	1956	(d)	(d)	4794	8397
	Cost $/1000 bu	(d)	48.90	(d)	(d)	11.98	20.99

(a)Based on average life of 3000 hours for COB units, unknown for Holec
(c)Original catalyst life exceeds 15 year life of generator
(d)No catalyst life data available for Holec
(d)Capacity insufficient for number of bushels in storage and time available for generating

The cost of liquid nitrogen flushing is given in Table 4. The hardware for this system consists of a permanently installed copper supply tube and homemade vaporizer constructed from rigid copper tubing, the total cost of which averages $7.50 per 1000 bushels flushed. The total cost of using the liquid nitrogen flushing system, therefore depends almost entirely upon the unit price and total consumption of liquid nitrogen. The present cost of liquid nitrogen, purchased in 160 liter Dewars delivered to the storage is 40 cents per liter in New York State. This price includes a three day demurrage charge for the Dewars.

The quantity of liquid nitrogen used varied greatly in the survey. We performed a nitrogen flushing experiment in May of 1985 on a filled, newly opened and totally ventilated 8,000 bushel CA room and found the 127 liters of liquid per 1,000 bushels was used to reduce the oxygen concentration from 21% to 5%. The storage operators report a use of liquid nitrogen ranging form 75 to 200 liters per 1,000 bushels.

Discussion

The survey data for fuel usage by various CA generators exhibited a large amount of variability. Since fuel use directly affects the operating cost, we have compared the theoretical fuel use with the actual values reported by the storage operators in Table 5. The largest range of values occurred with the Tectrol machines, some of which were old (1960's vintage) or used on very leaky CA rooms. The survey data indicated that some of the older Tectrol machines introduced excess air into the room through the CO_2 scrubber which normally operates during generation. The net result of these operating difficulties was an increased operating cost and reduced capacity for the generator. If Tectrol fuel use is 26.5 pounds per 1,000 bushels, the total generating costs shown in Table 3 increase by approximately 8% but the generator capacity is reduced by nearly 25%. The most significant impact of inefficient operation, therefore, is not the total cost, but the timeliness of CA establishment and the subsequent fruit quality coming out of storage.

The higher than theoretical fuel use values for the COB-1 and COB-3 units was due in part to imprecise survey data since these rooms were very tight. The fuel input rate to these machines during operation is varied to match the oxygen concentration of the recirculated atmosphere and some operators could not accurately estimate the rate of fuel usage during the period of generator operation or the exact time the units were in operation on a given CA room. Some operators turned the generators off at night when no one was attending them, but were unsure of the exact time of day when this occurred. If the theoretical fuel use of 7.3 pounds per 1,000 bushel were used instead of 12 pounds per 1,000 bushel as reported, utility cost for the COB-1 and COB-3 would decrease by roughly $3.30 per 1,000 bushel. Data for the COB-6 and Holec-50 units closely parallel the theoretical operation.

Table 4. Cost of Liquid Nitrogen Flushing

Usage Category	Minimum	Average	Maximum
Number in Survey	18	13	10
Nitrogen Use, 1/1000 bu(a)	75	120	200
Nitrogen Cost, $/1000 bu(b)	30	48	80
Annual Fixed Cost, $/1000 bu	1.02	1.02	1.02
Total Annual Cost, $/1000 bu	31.02	49.02	81.02

(a)For a reduction of oxygen from 21 percent to 5 percent
(b)At 40 cents per liter

Table 5. Fuel Use Comparisons for CA Generators Used to Reduce Oxygen from 21 Percent to 5 Percent

Generator	Tectrol	Wilde	COB-1	COB-3	COB-6	Holec-50
Theoretical Fuel Use #/1000 bu	15.4	15.4	7.3	7.3	7.3	17.7
Reported Use Range #/1000 bu	21.1-26.6	11.2	12	12	7	18.9

Data for liquid nitrogen use varied tremendously. Part of this variation is due to the tightness of the room and the rate of nitrogen introduction. In our trials of May of 1985, we found that very rapid atmosphere establishment resulted in the most efficient use of the liquid nitrogen. In our trials, we were able to reduce the oxygen concentration in an 8,000 bushel room from 21% to 5% in less than two hours. The cost of liquid nitrogen also varies from location to location. Since the cost of using nitrogen for room flushing is almost totally dependent upon the purchase price of the liquid, the actual cost in other geographical areas can be easily computed from the cost per liter.

Factors other than cost must be considered in selecting new or replacing old atmosphere generating systems. One major concern not indicated in the cost analysis is safety, which is discussed in reference 2. An obsolete machine may be inexpensive to operate but dangerous to use and this must be a consideration in generator replacement.

The use of propane fueled generators has not been compatible with low ethylene storage procedures (1) and if low ethylene storage is comtemplated, either the Holec or liquid nitrogen flushing system will be required. Liquid nitrogen may also be preferable as a substitute method where only one or two low ethylene rooms would be operated in a large multi-room storage complex.

The rate of atmosphere establishment is an additional factor in generator cost and efficiency. We are currently emphasizing the use of rapid CA and smaller CA rooms to hasten room filling in the fall and emptying in the spring. The generator should, therefore, be selected on a basis of both cost and capacity. It may not be possible to simultaneously provide rapid CA in numerous small rooms if only one generator is available for the task.

Note

Mention of any product, brand or trade name does not constitute endorsement of that product by the authors or Cornell University. Omission of any competitors' products similarly does not imply discrimination against those products. Specific product names are used to identify specific types of equipment and operating principles.

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