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ANALYSIS AND DEVELOPMENT OF A SOLAR ENERGY
REGENERATED DESICCANT CROP DRYING FACILITY

Phase I. Final Report, July 1976—April 1977

By
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J. W. Fletcher

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Lockheed Missiles and Space Company, Inc.
Huntsville, Alabama

U. S. DEPARTMENT OF ENERGY

Division of Energy Storage Systems

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OF A SOLAR ENERGY REGENERATED DESICCANT
CROP DRYING FACILITY**

Phase I

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JULY 1976 — APRIL 1977**

**S. M. Ko
D. V. Merrifield
J. W. Fletcher**

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FOREWORD

This document presents the results of the Phase I study of a solar regenerated desiccant crop drying facility under Contract E(40-1) 5157 for the U.S. Energy Research and Development Administration (ERDA), and includes design concepts and data developed under Contract USDA-12-14-7001-817 for the U.S. Department of Agriculture, Agricultural Research Service (ARS/USDA).

The study was performed by personnel of Lockheed-Huntsville Research & Engineering Center, Huntsville, Alabama. The Program Manager for ERDA is Mr. C.J. Swet of the Division of Energy Storage Systems, ERDA Headquarters. The Technical Monitor is Dr. Herbert Hoffman of the Oak Ridge National Laboratory.

The authors are grateful to the following personnel for their contributions to this study: Dr. G.H. Watson, Union Carbide Corporation, Oak Ridge, Tennessee (formerly of Lockheed-Huntsville); Dr. J. L. Butler, USDA/ARS, Tifton, Georgia, for his valuable direction in crop drying technology, and; Dr. L. B. Altman, USDA/ARS, Beltsville, Maryland, for his encouragement and interest in this program and especially for his comments and recommendations on the economics analysis.

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ABSTRACT

This report documents the results of a study to verify the technical feasibility of the regenerated desiccant crop drying concept, characterize its performance, investigate design requirements, and define a pilot facility for further evaluating the operational and energy-conservative characteristics of the drying system. The pilot facility defined in this study will be a useful R&D tool of sufficient size to permit a meaningful evaluation of the system and to provide the necessary criteria for development of full-scale systems.

The principal finding of the study is that the regenerated desiccant crop drying concept is technically feasible and has the capability to achieve a drying efficiency of approximately twice that of conventional crop drying systems. When using a fossil fuel energy source, energy savings will be approximately 40 to 50%. With solar energy input, the total fossil fuel savings could be 70 to 90%. The economic feasibility of the system appears promising. As with other new energy conserving systems that are presently capital-intensive, the economic viability of the system will be dependent on future capital cost reductions, on the future price of fossil fuels, and on the specific application of the system. Regarding system applications, it was concluded that the regenerated desiccant drying system, with or without the use of solar energy, will be economically best suited for a large central processing application, where it can receive a maximum amount of use and will benefit from economy-of-scale cost considerations.

The basic study recommendations are: (1) additional R&D activities should be conducted to identify and evaluate means for achieving system cost reductions, and (2) the Mobile Pilot Facility program should be initiated.

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Section 1

INTRODUCTION AND SUMMARY

The drying of agricultural products in the United States consumes more than 10^{14} Btu per year of fossil-fuel energy (Ref. 1) or the equivalent of 17.2 million barrels of oil. When industrial drying is added, the estimated annual energy expenditure for drying is 10^{15} Btu. Future means for reducing this expenditure of energy through development of more efficient drying techniques and the use of solar energy are therefore highly desirable. The regenerated desiccant crop drying concept being investigated under this particular ERDA contract is one which can reduce crop drying energy expenditures by 40 to 50% compared to conventional widely used heated-air drying techniques. The use of solar energy can further reduce the fossil fuel energy requirements. In addition, the drying technique can be applied to a variety of industrial applications.

This report documents the results of a study to verify the technical feasibility of the concept, characterize its performance, investigate design requirements, and define a pilot facility for further evaluating the operational and energy-conservative characteristics of the drying system. The pilot facility defined in this study will be a useful R&D tool of sufficient size to permit a meaningful evaluation of the system and to provide the necessary criteria for development of full-scale systems.

The present study of a solar-regenerated desiccant crop drying system has resulted in confirmation of the energy-conservative feature of the concept as originally predicted and has provided a good degree of confidence that the system can be successfully commercialized. The study also revealed that the economic feasibility of the system will be enhanced by future improvements in capital cost and by maximizing its amount of annual use.

Major tasks accomplished in this study phase included: (1) establishment of crop drying requirements which influence the design of the system; (2) study of system/process configurations and establishment of a baseline design concept; (3) analysis, mathematical modeling, and parametric study of the system; (4) laboratory test and evaluation of a bench-scale experimental demonstration system; (5) parametric evaluation of the economic characteristics of the system; (6) investigation of process control requirements; (7) definition and costing of a pilot-scale drying system; (8) analysis of system applications; and (9) definition of an approach to achieving commercial utilization.

Process analysis and modeling of the selected system, which uses a lithium chloride desiccant solution, showed that under optimum control conditions, it can achieve a specific energy input of as low as 800 Btu/lb of water removed from the crop. This compares with approximately 2000 Btu/lb for a conventional dryer without heat recovery (Ref. 17). As with all of the process concepts studied, the high efficiency is obtained by using both the reclaimed latent heat of condensation available from the water vapor, and the sensible heat contained in the regenerated desiccant. Study of process control requirements for the system showed that optimal control and regulation of process parameters can result in significant improvements in system capacity and energy input.

Test and evaluation of the bench-scale experimental system provided laboratory evidence that the regenerated desiccant drying concept is technically feasible and can achieve the predicted energy efficiency. The performance obtained was within 10% of the predicted performance and provided a good demonstration of the accuracy and validity of the analytical modeling techniques developed.

Regarding the use of solar energy for regenerating the desiccant, there is no doubt as to the technical feasibility of doing so. As to the best application for a regenerated desiccant crop drying system or facility, it became

evident during the study that a central processing application, in which the system receives a maximum amount of use, will provide the most favorable economics. It is also evident that more work needs to be done to identify specific applications for which the concept is best suited.

As an integral part of the study, a pilot-scale drying facility was defined and costed. As a self-contained mobile system with a 50 bu drying capability, it will represent a valuable R&D facility with which to perform in-depth evaluation of the system and develop design criteria for a commercial-size system.

The basic study recommendations are that additional R&D studies be performed to evaluate methods for improving the cost effectiveness of the system, and that the Mobile Pilot Facility program be initiated.

Section 2

BACKGROUND

Study of solar regenerated desiccant drying processes for agricultural applications was initiated by Lockheed in early 1976 under USDA sponsorship (Ref. 2) and has continued under ERDA sponsorship since August 1976. The motivation for this research originated from the results of pre-contract studies which indicated that a significant degree of fossil fuel conservation could be achieved with respect to conventional crop drying techniques. This was shown to be potentially achievable through: (1) a high efficiency desiccant drying process, and (2) the use of solar energy as a prime or auxiliary energy source. In the USDA study (Ref. 2) both solid and liquid desiccants were examined and characterized with respect to thermal properties, water affinity, regeneration temperature, toxicity, corrosion properties, stability and cost. Process concepts were generated and evaluated for energy efficiency and drying effectiveness. In each case, the energy conservative feature was to reclaim the heat of vaporization of the moisture removed from the desiccant and make maximum use of the energy required for the overall drying process. The specific concept which emerged as being the most attractive for evaluation as a baseline concept under the ERDA contract is based on the use of an aqueous solution of lithium chloride. This desiccant, although more expensive than the others considered, has favorable physical properties and is particularly effective for drying delicate crops such as seed corn, peanuts, soybeans and rice. Calcium chloride is a less expensive alternate but does not have the wide range of applicability that lithium chloride has. The properties of several alternative liquid desiccants are tabulated in Appendix A.

The general process scheme which was evolved and studied in conjunction with lithium chloride desiccant is shown in simplified form in Fig. 2-1. This is presented not only to explain the basic operation of the crop drying concept but to show its general applicability in drying of either agricultural

Fig. 2-1 - Schematic of Regenerated Desiccant Dryer Concept

or industrial products. The desiccant dryer is comprised of three main elements: an absorption loop in which moist air from the crop bin is dehumidified by the liquid desiccant and dry air is supplied to the bin (closed cycle chemical drying); a regeneration loop which removes the water which was added to the desiccant but retains its heat of condensation, and a desiccant storage tank. The energy source may be either solar, fossil, or a combination of both. The heart of the system is the regeneration loop; it uses heat at 200 to 270 F to regenerate (remove water from) the dilute desiccant and delivers lower grade heat which can be used for either open cycle thermal drying or can be furnished as process heat for a non-drying use. Note that the only heat rejected from this cyclic process is that used for open-cycle drying (30 to 40% of total drying capacity) or that used for the process heat option. In Section 3.1 the process is described more fully in regard to operating modes and design options.

Section 3

TECHNICAL AND ECONOMIC FEASIBILITY STUDY (SYSTEM ANALYSIS)

To evaluate the feasibility of the regenerated desiccant crop drying concept and establish its performance and design characteristics, a system analysis was conducted. This consisted of establishing system requirements, selecting a baseline design concept and operating parameters, developing mathematical models of the system and its components, defining and characterizing a bench-scale laboratory system and a mobile pilot facility, investigating process control requirements, analyzing potential end uses for the system, and determining an approach to achieving commercial utilization.

The regenerated desiccant drying concept differs from conventional crop drying techniques primarily in the method of supplying dry air (low relative humidity) to the product (crop or grain) to be dried. For this reason, major study emphasis was placed on analyzing the design and performance characteristics of the absorption loop and regeneration loop, with the latter receiving the principal emphasis since it is the energy-using portion of the drying system. Studies on the drying process were performed to the extent necessary to determine drying requirements and moisture removal characteristics.

3.1 SYSTEM REQUIREMENTS AND PROCESS DEVELOPMENT

3.1.1 Drying Requirements

Moisture is removed from crops in order to achieve safe storage. Excessive moisture content in crops causes the growth of molds and attracts insects. Approximately 5 to 8% loss occurs from the spoilage.

The moisture content of crops during harvest is typically 20 to 35% and the moisture content for safe storage is in the range of 11 to 13% (as shown in Table 3-1) for several selected crops. This means that typically 50% of the moisture contained in the crop when harvested must be removed to meet the safe storage requirement.

Table 3-1
MOISTURE CONTENT DURING HARVEST
AND FOR SAFE STORAGE (REF. 3)
Percent Wet Basis (W.B.)

Crop	Maximum During Harvest	Optimum at Harvest for Minimum Loss	Usual When Harvested	Required for Safe Storage	
				for 1 yr	for 2 yrs
Barley	30	18-20	10-18	13	11
Corn	35	28-32	14-30	13	10-11
Oats	32	15-20	10-18	14	11
Peanuts	60	—	35-45	10*	10*
Rice	30	25-27	16-25	12-14	10-12
Rye	25	16-20	12-18	13	11
Sorghum	35	30-35	10-20	12-13	10-11
Wheat	38	18-20	9-17	13-14	11-12

*Dr. J. L. Butler, USDA/ARS, Tifton, Georgia, personal communication.

Various parameters influence the drying process. These include air relative humidity, air temperature, air flow rate, initial moisture content, and final moisture content. Among these parameters, the most important is the relative humidity of air used in the drying process. The relative humidity of the inlet air to the drying bin must be lower than the equilibrium relative humidity of the crop at its final moisture content (required safe storage moisture content) to be achieved by the process. In other words, the equilibrium moisture content (EMC) of the crop at the inlet air condition must be lower than the desired final moisture content of the crop. EMC is

defined as the moisture content of a crop after it has been exposed to a particular environment for an infinitely long period of time. Experimentally measured EMCs for various crops are available in Appendix B. For most crops, the EMC is lower than the safe storage moisture content for 35 to 45% relative humidity air. Therefore, a drying system must be capable of delivering 35 to 45% relative humidity to dry a crop to a safe storage moisture content.

In a conventional drying system, ambient air is heated to suppress the relative humidity to the required level. Figure 3-1 illustrates the heating requirement necessary to drop the relative humidity of the ambient air to 30%. Point A in the figure represents a typical summer ambient air condition (95 F, 80% R.H.). The drying of corn, a summer crop*, is an example of this case. Corn is usually dried at relatively high temperatures, 120 to 160 F. On the other hand, fall crops* such as peanuts and rice, are usually dried at lower temperatures. It should be noted, however, that the drying temperature is determined by the physical/chemical characteristics of the crop rather than the harvesting season. Point B represents a typical ambient condition (70 F, 70% R.H.) in the fall.

High temperature is not required to dry a crop, although it has a small effect on the drying process due to the decreasing equilibrium moisture content with increasing drying temperature. The EMC is a function of both the relative humidity and the temperature. However, the temperature effect is small as compared to that of relative humidity.

The drying temperature is a significant factor in the quality of the crop. Due to the quality deterioration caused by high temperature drying, the temperature of drying air must be kept below certain maximum depending on the type of crop and the intended uses of the crop. The maximum safe temperatures of the heated air for different intended uses are tabulated in Table 3-2. At higher temperature (lower relative humidity), the drying time required is shorter, and this is the reason for using high temperature when the intended use of the crop is for animal feed. The drying temperature range in Table 3-2 is 90 to 180 F, and this corresponds to relative humidity of 60 to 10%.

* In Texas, peanuts are harvested in July. Corn may be, and the bulk is, harvested later than peanuts or rice.

Fig. 3-1 - Conventional Drying Process (A) Summer Drying (Corn)
(B) Fall Drying (Peanuts, Rice)

In the previous USDA study (Ref. 2), it was revealed that lithium chloride solution is capable of delivering 10 to 60% relative humidity air and was selected as the most promising desiccant for crop drying applications. The use of lithium chloride as a desiccant limits the maximum drying temperature to a lower range, 90 to 100 F, of conventional drying practice listed in Table 3-2, because of constraints on removing moisture from the drying air in the absorption process. To achieve potential to remove water vapor from the drying air in the absorption process, the temperature of the desiccant must be maintained below 100 F. The partial pressure of water in the desiccant must be lower than the partial pressure of water vapor in the air in order to generate a potential for the mass transfer of water from air to desiccant, thus the constraint on desiccant temperature. The partial pressure of water is a strong increasing function of desiccant temperature as shown in Fig. 3-2.

Table 3-2
MAXIMUM SAFE DRYING AIR TEMPERATURE (REF. 4)

Crop	Maximum Temperature for		
	Seed	Commercial Use	Animal Feed
Corn	110	130	180
Wheat	110	140	180
Oats	110	140	180
Barley	105	105	180
Grain Sorghum	110	140	180
Soybeans	110	120	—
Rice	110	110	—
Peanuts	90	90 to 100	—

Fig. 3-2 - Operating Range of Lithium Chloride Desiccant for Crop Drying

Drying crops at low temperature has a number of inherent advantages. It is desirable to avoid damage to the crop as a result of thermal stresses both during the drying process as well as during cooling of the crop at the conclusion of drying. Also, the thermal losses are reduced when the temperatures throughout the drying equipment are maintained at low temperature. Furthermore, low temperature drying is mandatory for more delicate crops such as peanuts, rice, tobacco and various seed crops to preserve quality of the dried product. These crops are considered relatively difficult and expensive to dry in a conventional dryer, and thus are particularly suited for the regenerated desiccant crop drying system discussed in this report.

3.1.2 Concept Development

The process system for the regenerated desiccant crop drying concept requires several unit operations:

1. Dehumidification of the moist air from the crop bin,
2. Heating the dehumidified air to adjust relative humidity and drying temperature,
3. Cooling the dilute desiccant resulting from the dehumidification (absorption) of the moist air,
4. Heating the desiccant to the desired regeneration temperature,
5. Stripping the moisture from the heated dilute desiccant,
6. Recouping the heat of vaporization (latent heat) expended in the stripping, and
7. Utilizing excess sensible heat contained in the hot regenerated desiccant.

These unit operations can be combined into two flow loops, an absorption loop and a regeneration loop. The first three are performed in the absorption loop and the rest are in the regeneration loop. Figure 3-3 is a schematic diagram which shows process equipment necessary in accomplishing each of the unit operations listed above.

Fig. 3-3 - Process Block Diagram of Desiccant Crop Drying System

For each unit operation, several process design concepts that affect the system efficiency and economics were initially investigated. They included:

- Steady state versus transient operation of absorption (dehumidification) process and stripping process — steady state operation implies the use of two desiccant storage tanks, one for dilute (used desiccant and the other for concentrated (regenerated) one, while transient operation required more sophisticated control system. Figure 3-4 presents the steady state option with two tanks.
- Isothermal versus nonisothermal operation of absorption column — the dehumidification process is an exothermic process and requires an external cooling stream to operate it under isothermal conditions. The isothermal operation ensures more efficient removal of the moisture from the air.
- Solar energy as a primary or auxiliary versus fossil fuel only as energy source for regeneration. In case of solar energy utilization, the desiccant storage tank can be used for thermal energy storage, chemical storage, or both. Use of the solar system can further reduce the fossil energy requirements.
- Stripping column versus evaporator as the regeneration equipment — In both cases a condenser is used to recoup the heat of vaporization. With the evaporator, the condenser can be operated more efficiently due to the absence of noncondensables in the vapor stream from the column to the condenser. However, the removal of noncondensables requires additional evacuating means. Figure 3-5 shows the evaporator concept. This system has a very promising potential in reducing regeneration system cost, although it requires analytical and experimental study.
- Intermittent regeneration versus continuous regeneration — continuous regeneration does not require a desiccant storage tank, but energy cannot be stored for later use. This poses a problem in the maximum utilization of solar (stored as hot desiccant) energy. An additional study should be in order to develop an optimum level of solar energy utilization.

Fig.3-4 - Desiccant Drying Concept with Steady State Operation of Columns

Fig. 3-5 - Desiccant Drying Concept with Evaporative Regeneration System

- One or two batch bins versus continuous flow column dryer — The excess sensible heat from the regeneration operation can be used either in the drying process or to provide process heat as necessary in a large central processing plant application. As an in-process utilization option, the thermal energy can be used for heating ambient air to provide dry air to the bin, expending the resulting moist air to the atmosphere. This is an open cycle drying operation that is analogous to the conventional heated air drying. Two batch bins are required for continuous regeneration. A two-stage continuous flow column dryer can be used in the place of two batch bins. A schematic process flow diagram for this concept is presented in Fig. 3-6. This concept has potential for large-scale application.

System analyses of these process options were conducted to select a baseline system for detailed investigation through laboratory proof-of-concept experiments and a pilot-scale system to demonstrate the concept and to obtain detailed design requirements for a full-scale facility. The selection criteria were:

- System simplicity
- Ease of operation
- Dual mode operation — solar or fossil
- Low maintenance
- Intermittent regeneration
- Ready availability of system components — off-the-shelf equipment

The baseline system process flow diagram is shown in Fig. 3-7. This system incorporates a batch bin suitable for both open cycle and closed cycle modes of drying operation, an absorption column (transient operation), an L/G heat exchanger (desiccant/air) used for both open and closed cycle modes, a desiccant storage tank, a stripping column (transient operation), a smooth tube condenser for recouping heat of vaporization, a regenerative L/L heat exchanger (desiccant/desiccant) to preheat the dilute desiccant and to cool the regenerated

Fig. 3-6 - Desiccant Drying Concept with Two-Stage Continuous Column Dryer

Fig. 3-7 - Baseline Regenerated Desiccant Crop Drying Concept

desiccant, and a solar energy collector and a conventional heat source to provide required thermal energy for the regeneration process. In the following section, a detailed process analysis of the baseline system is presented.

3.1.3 Process Analysis

a. Absorption Loop/Closed Cycle Drying

Figure 3-8 shows schematically the closed cycle drying operation and the absorption loop operation. The upper half is for the closed cycle drying and the lower half shows the corresponding changes in the desiccant concentration and temperature. In the drying bin, the drying air picks up the moisture from the crop and is humidified (i.e., $A \rightarrow B$ in the diagram). The drying process requires energy to drive the moisture from the crop, and this energy is provided by the drying air. Therefore this humidification process follows the adiabatic cooling path on the psychrometric chart. The dehumidification process (i.e., $B \rightarrow C$) is an exothermic process, accomplished in the absorption column, and hence the air is heated to some extent but not quite back to the drying temperature. Although the absolute humidity is the same for C and A, the air at C must be heated ($C \rightarrow A$) to suppress the relative humidity and thereby the cycle is completed. The required energy for this heating is provided by the dilute hot desiccant from the column (i.e., process (b) in the lower diagram). The process (b) is a cooling process for the used desiccant. The desiccant is heated in the absorption process (a) and the excess sensible energy is used for open-cycle drying. The absorption process is a transient one due to continuous change in the concentration of the desiccant to the column. C_1 is the initial concentration and C_2 is the final one when the closed cycle drying operation is completed. The cycle (a') - (b') - (c') represents an intermediate condition when the tank concentration is at C_3 .

b. Regeneration Loop/Open Cycle Drying

Figure 3-9 shows schematically the operation of the open cycle drying in the upper diagram and the regeneration operation in the lower half. The

Fig. 3-8 - Changes of Process Parameters in the Absorption Loop (Closed cycle drying) Operation

Fig. 3-9 - Changes of Process Parameters in the Regeneration Loop (Open cycle drying) Operation

starting condition (D) for the regeneration is typically 37% at 90 F. The process (d) is a heating process to elevate the desiccant temperature to the regeneration temperature, T_4 (240 to 250 F) and is accomplished in three steps: (1) heating from T_1 to T_2 is done in the condenser by recovering heat of vaporization; (2) the desiccant is further preheated from T_2 to T_3 in an L/L heat exchanger using the hot regenerated desiccant stream from the stripping column ($T_3 \rightarrow T_2$ portion of cooling process (f) in the diagram); and (3) a solar collector or a conventional heater is used to heat it from T_3 to T_4 . The thermal energy in this process ($T_3 \rightarrow T_4$) is used in the stripping process (e) to drive out the moisture from the dilute hot desiccant, which results in cooling of the desiccant from T_4 to T_3 . To complete the cycle and to use the regenerated desiccant again as a coolant in the condenser until the tank concentration reaches to the desired level, the temperature of the regenerated stream must be suppressed to the tank temperature, T_1 . This is performed in two steps: (1) the desiccant is cooled to T_2 in the L/L heat exchanger to preheat the dilute desiccant (process (d) $T_2 \rightarrow T_3$) as described earlier, and (2) the desiccant is cooled from T_2 to T_1 , which is accomplished in the L/G heat exchanger to provide dry air for the open cycle drying. The net result is that the energy input to the regeneration system (heating T_3 to T_4 in (d)) is recovered and is available as the energy output of the regeneration loop in the form of lower quality energy (cooling T_2 to T_1 in (f)), which can be readily used as energy source for the open cycle drying. Due to the transient characteristic of the stripping column operation the cycle is repeated until the tank concentration reaches to C_1 . The cycle (d') - (e') - (f') - (g') represents an intermediate regeneration cycle. In the upper diagram, the ambient air at E (65 F, 85% R.H.) is introduced to the L/G heat exchanger and heated to suppress the relative humidity using the available sensible energy from the regenerated desiccant. The process F to G represents the drying process. In this process, the air is humidified, which follows the adiabatic cooling path on the psychrometric chart, and is expended to the atmosphere at almost saturated condition. The process E' - F' - G' is basically the same as the E - F - G path except that the ambient temperature at E' is higher than that of E. The open cycle drying operation largely depends on the ambient air condition. In particular, for

the worst summer time condition, 90% R.H. at 95 F for example, the ambient air must be heated up to 125 F in order to suppress the relative humidity down to 40%. This still can be accomplished in the L/G heat exchanger since the temperature of the regenerated desiccant available is in the range of 140 to 150 F. However, the maximum drying temperatures for certain crops, for example peanuts and rice, are lower than 125 F and therefore humid summer day ambient air is not favorable for open cycle drying.

c. Material and Energy Balance

A material and energy balance has been made for the baseline process system. All the process parameters were determined on an hourly basis based on 1 Bu/hr drying capacity. An 18-hr drying cycle was assumed with a 6-hr open cycle drying and 12 hrs of closed cycle drying. Peanuts were selected as the basic crop for 10 points removal (i.e., 20 to 10%). The six hour open cycle drying (regeneration) is a constraint imposed by the use of solar energy. Typically, peanuts are dried in 20 to 36 hrs.

Table 3-3 is a summary of the overall material balance. The drying rate during the open cycle is 7.11 lb/hr and 5.37 lb/hr is the rate for the closed cycle mode. This is equivalent to 107 lb moisture removal per cycle. The drying rate for the open cycle is higher than that for the closed cycle by 32% for the maximum utilization of thermal energy available from the regeneration operation. Equal drying rates can be achieved by simply extending the duration of the regeneration and hereby reducing the supply of thermal energy for the open cycle drying.

Table 3-4 summarizes results of the energy balance. The net energy input to the system is 14,269 Btu/hr supplied by the heater (solar or fossil), which is 85,614 Btu/cycle. The specific energy input per pound of moisture removed from the crop is 800 Btu/hr. There is no net energy requirement for the closed cycle drying, that is, the energy expended in the bin is recovered in the absorption column. The energy required for the closed cycle

Table 3-3

SUMMARY OF OVERALL MATERIAL BALANCE FOR THE BASELINE SYSTEM
(1 BU/HR PEANUTS, 10 POINTS REMOVAL)

Equipment	Process Streams		Input (lb/hr)	Output (lb/hr)	Mass Transfer To Air (lb/hr)	Mass Transfer To Desiccant (lb/hr)
Stripping Column	Desiccant	LiCl H ₂ O	134.8 215.2 350.0	134.8 204.26 339.26		-10.74
	Air	Air H ₂ O	50.0 6.8 56.8	50.0 17.54 67.54	+ 10.74	
Condenser	Air	Air H ₂ O	50.0 17.54 67.54	50.0 6.8 56.8	- 10.74	
	Condensate		—	10.74		
Bin	Open Cycle	Ambient Air	Air H ₂ O	1871.1 21.9 1893.0	1871.1 29.01 1900.11	+ 7.11
		H ₂ O from Crop	7.11	—		
	Closed Cycle	Air	Air H ₂ O	1413.2 16.53 1435.1	1413.2 21.9 1435.1	+ 5.37
		H ₂ O from Crop	5.37	—		
Absorption Column	Desiccant	LiCl H ₂ O	192.5 307.5 500.0	192.5 312.87 505.37		
	Air	Air H ₂ O	1413.2 21.9 1435.1	1413.2 16.53 1429.73	5.37	+ 5.37

Table 3-4

SUMMARY OF OVERALL ENERGY BALANCE FOR THE BASELINE SYSTEM
(1BU/HR PEANUTS, 10 POINTS REMOVAL)

Equipment		Process Streams	Input Btu/hr	Output Btu/hr	Heat Transfer To Air Btu/hr	Heat Transfer To Desiccant Btu/hr
Stripping Column		Desiccant Air Total	47,320 8,096 <u>55,416</u>	33,734 21,682 <u>55,416</u>	+13,586	-13,586
Condenser		Desiccant Air Condensate Total	13,195 21,682 — <u>34,877</u>	26,106 8,096 677 <u>34,877</u>	-13,586	+12,909
L/L Heat Exchanger		Desiccant (dil.) Desiccant (reg.) Total	26,104 33,734 <u>59,838</u>	33,051 26,787 <u>59,838</u>		+ 6,947 - 6,947
Heater		Desiccant Energy Input Total	33,051 14,269 <u>47,320</u>	47,320 — <u>47,320</u>		-14,269*
L/G Heat Exchanger	Open Cycle	Ambient Air Desiccant (reg.) Heat Loss Total	38,139 26,787 — <u>64,926</u>	49,612 12,740 2524 <u>64,926</u>	+11,473	-13,977
	Closed Cycle	Air Desiccant Total	34,454 21,855 <u>56,309</u>	37,459 18,850 <u>56,309</u>	+ 3,005	- 3,005
Bin	Open Cycle	Dry Air Moisture Total	26,046 23,566 <u>49,612</u>	18,629 30,983 <u>49,612</u>	- 7,417	
	Closed Cycle	Dry Air Moisture Total	19,671 17,788 <u>37,459</u>	14,070 23,389 <u>21,855</u>	- 5,601	
Absorption Column		Desiccant Air Total	18,850 37,459 <u>56,309</u>	21,855 34,454 <u>56,309</u>	- 3,005	+ 3,005

* Net input to system.

drying is supplied by the warm, used desiccant. The specific energy requirement for the open cycle drying is 1,968 Btu per lb moisture removed during the open cycle, which is comparable to the conventional energy requirement. This can be improved by reducing the heat loss involved in the heat transfer process. The heat loss is estimated at 18% of the available energy to the L/G heat exchanger. The ambient air condition is assumed to be 65 F at 90% R.H.

3.2 PARAMETRIC STUDY

Mathematical models for various system components were developed to simulate the performance of the process, and to characterize various process parameters and design criteria.

3.2.1 Description of Mathematical Models

a. Batch Drying

Moisture is held by the crop as free water and bound water within the molecular structure of the kernel. Free water is easily evaporated early in the drying process. Removal of bound water requires that the water be diffused through the kernel to the surface before evaporation can take place. Drying is typically slower for removal of bound water, thus the moisture removal rate decreases with drying time. This is referred to as the "falling rate period." Mathematical models for describing the rate of drying in a batch drying bin often use empirical expressions for the drying rate of a thin layer of crop within which the crop properties are homogeneous. The rate of drying is equated to an expression involving properties of the crop and the drying air. By dividing the crop batch into a number of thin layers the moisture content of the crop may be predicted as a function of depth and time.

A semi-empirical expression for a batch dryer developed by Hukill (Ref. 5) is given by the equation shown on the following page.

$$M(D, \theta) = M_e + (M_o - M_e) \frac{2^D}{2^D + 2^\theta - 1} \quad (3.1)$$

where D and θ are the dimensionless depth unit and the time unit, respectively. M_e is the equilibrium moisture content for the inlet air to the batch, and M_o is the initial moisture content of the crop. One depth unit contains a quantity of dry matter that can be dried to the final moisture content in half the drying time, $t_{\frac{1}{2}}$. $t_{\frac{1}{2}}$ is the drying time required to dry the crop in a very thin layer from a moisture ratio of 1.0 to 0.5.

A heat balance around the bin gives

$$D = \frac{Z G C_a D_B (T_G - T_{GW}) t_{\frac{1}{2}}}{P_M (H_{vap} (M_o - M_e))} \quad (3.2)$$

where Z is the height from the bottom of the bin, D_B is the depth of bin, C_a is the heat capacity of air, G is the air flow rate (dry basis). T_G and T_{GW} are dry and wet bulb temperature of the air, P_M is the dry weight of the crop to be dried and H_{vap} is the heat of desorption of the moisture required in the drying process. $t_{\frac{1}{2}}$ may be obtained from published experimental data (Refs. 6, 7).

Henderson's semi-empirical expression (Ref. 8) was used to obtain an equation for the equilibrium moisture content as a function of relative humidity and temperature,

$$M_e^n = - \frac{\ln(1 - r.h.)}{C T_{abs}} \quad (3.4)$$

where C and n are constants for a given crop and may be calculated from published experimental data (Ref. 9 and Appendix B).

A material and energy balance for the control volume gives the model summarized in Fig. 3-10.

$$\frac{\partial Y}{\partial Z} = \frac{\rho_P S}{G} \frac{\partial M}{\partial t}$$

$$\frac{\partial T_G}{\partial Z} = - \frac{H_{\text{vap}} \frac{\partial M}{\partial t} \rho_P S}{C_a G}$$

$$\frac{\partial M}{\partial t} = - \frac{\ln 2 (M_o - M_e) 2^D 2^\theta t_{1/2}}{(2^D + 2^\theta - 1)}$$

$$M_e^n = \frac{\ln(1 - r.h.)}{C T_{\text{abs}}}$$

$$D = \frac{D_B G_T C_a (T_G - T_{GW}) t_{1/2}}{P_M H_{\text{vap}} (M_o - M_e)}$$

$$\theta = t/t_{1/2}$$

Fig. 3-10 - Summary of the Batch Drying Model

b. Absorption and Stripping Columns

The thermal and chemical state of the desiccant will float with time because the removal of moisture from the air both in the absorption and stripping columns will dilute or concentrate the desiccant which affects the absorbability or regenerability. The time dependent variations in the desiccant state during regeneration and absorption modes of operation may be predicted by modeling the mass transfer and heat transfer processes occurring in the packed columns. Figure 3-11 is a summary of the model described in the following paragraphs.

The packed columns are filled with packing material in order to increase the specific transfer area for the transfer of water from air to desiccant or vice versa. Consider an incremental height of packing, dZ , which has a transfer area of adZ . The mass transfer rate between the gas and liquid phases may be expressed as

$$- G_s dY = k_Y a (Y - Y_i) dZ = k_Y a (Y - Y_i^*) dZ \quad (3.5)$$

where G_s is the air flow rate per unit area of the column, k_Y is the gas phase mass transfer coefficient, Y_i is the humidity at the interface, and Y_i^* is the equilibrium humidity. The mass transfer coefficient may be obtained from an appropriate empirical equation expressed as a function of dimensionless groups (Refs. 10, 11 and 12). For simplicity of the model, the following assumptions were made: (1) the diffusion of water vapor is controlled by the gas phase; (2) the process is under quasi-steady state; (3) physical properties are constant; (4) the distribution of the flow is uniform, and there is no axial dispersion. From Eq. (3.5) we have

$$\frac{dY}{dZ} = - \frac{k_Y a}{G_s} (Y - Y_i^*) \quad (3.6)$$

$$\frac{dY}{dZ} = - \frac{k_Y a (Y - Y_i^*)}{G_s}$$

$$\frac{dX}{dZ} = - \frac{k_Y a (Y - Y_i^*)}{L_s}$$

$$\frac{dt_G}{dZ} = \frac{h_G a (t_i - t_G)}{G_s C_{SG}} - \frac{k_Y a (Y - Y_i^*) C_{AG} (t_i - t_G)}{G_s C_{SG}}$$

$$C_{EG} = C_{BG} + Y C_{AG}$$

$$\frac{dt_L}{dZ} = - \frac{h_L a (t_i - t_L)}{L_s C'_{SL}} - \frac{k_Y a (Y - Y_i^*) \{ C_{AL} (t_i - t_o) - C_{SL} (t_L - t_o) - \Delta H_{soln} \}}{L_s C'_{SL}}$$

$$C'_{SL} = (1 + X) C_{SL}$$

$$t_i = \frac{h_L t_L + h_G t_G + k_Y (Y - Y_i^*) \{ (C_{AL} - C_{AG}) t_o + \lambda_o + \Delta H_{soln} \}}{h_L + h_G + k_Y (Y - Y_i^*) (C_{AL} - C_{AG})}$$

Fig. 3-11 - Summary of the Packed Column Model

An overall mass balance between the liquid and gas phase requires

$$L_s dX = G_s dY$$

Hence,

$$\frac{dX}{dZ} = - \frac{k_Y a}{L_s} (Y - Y_i^*) \quad (3.7)$$

Now, the Z dependence of the gas temperature can be obtained from a gas phase energy balance;

$$\frac{dt_G}{dZ} = \frac{h_G a}{L_s C_{sL}} (t_i - t_G) - \frac{k_Y a (Y - Y_i^*) C_{AG} (t_i - t_G)}{G_s C_{sG}} \quad (3.8)$$

where $C_{sG} = C_{BG} + Y C_{AG}$

Similarly, an energy balance for the liquid phase gives

$$- \frac{dt_L}{dZ} = \frac{h_L a}{L_s C'_{sL}} (t_i - t_L) + \frac{k_Y a (Y - Y_i^*)}{L_s C'_{sL}} \left\{ C_{AL} (t_i - t_o) - C_{sL} (t_i - t_o) - \Delta H_{soln} \right\} \quad (3.9)$$

where $C'_{sL} = (1 + X) C_{sL}$.

An energy balance for the entire control volume gives

$$\begin{aligned} L_s C_{sL} (t_i - t_o) dX + L_s C'_{sL} dt_L &= G_s C_{sG} dt_G \\ &+ G_s \lambda_o dY + G_s C_{AG} (t_G - t_o) dY \end{aligned} \quad (3.10)$$

Dividing by dZ and substituting for dY/dZ, dX/dZ, dt_G/dZ and dt_L/dZ gives an expression for the interface temperature

$$t_i = \frac{h_G t_G + h_L t_L + k_Y (Y - Y_i^*) \lambda_o + \Delta H_{soln} + (C_{AL} - C_{AG}) t_o}{h_G + h_L + k_Y (Y - Y_i^*) (C_{AL} - C_{AG})} \quad (3.11)$$

The Z dependence of X, Y, T_G and t_L can be computed by integrating the Z derivatives through the column. This constitutes a simple initial value problem which is solved with an Euler integration. The integration is initiated at the bottom of the column where initial conditions for the gas phase, Y and t_G , are known. An estimate for the initial conditions on the liquid phase, X and t_L , is made. The Z-derivatives are integrated along the Z coordinate to the top of the column where final values for the liquid phase, X and t_L , are known. Values of X and t_L from the integration are compared with known values of X and t_L . If the known and the computed X and t_L differ by more than an acceptable amount (typically 1.0 F for t_L and 0.00005 for X), X and t_L are re-initialized at the bottom of the column until an acceptable match is achieved at the top of the column. When the known and integrated values of X and t_L are matched, the choice of initial values for X and t_L at the bottom of the column and the values of Y and t_G resulting from the integration of the Z-derivatives are considered valid.

c. Condenser

The moist air from the stripping column is fed to the condenser to condense the moisture out of the air and thereby to recoup the heat of vaporization. The dilute desiccant stream is used as a coolant and is preheated in the condenser.

The temperature of the desiccant at the outlet, the temperature and the humidity of the air, and the flow rate of the resulting condensate can be computed using a mathematical model. A summary of the mathematical model for the condenser is presented in Fig. 3-12.

A control volume of thickness dZ is considered. An overall mass balance may be written as

$$- G dY = k_Y (Y - Y^*) dA = dW$$

or

$$\frac{dY}{dA} = - \frac{k_Y}{G} (Y - Y^*) \quad (3.12)$$

$$\frac{dW}{dA} = k_Y (Y - Y^*)$$

$$\frac{dY}{dA} = \frac{k_Y}{G} (Y - Y^*)$$

$$\frac{dt_G}{dA} = \frac{h'_G (t_G - t_W)}{G C_{SGT}}$$

$$h'_G = \frac{-G C_{AGT} dY/dA}{1 - \text{EXP}\left[G C_{AG} \frac{dY}{dA} / h_G\right]}$$

$$h_G = 0.05151 (Gl/A)^{0.83} \frac{C_{SG}}{D(1+Y)^{0.17}}$$

$$\frac{dt_L}{dA} = \frac{h_L (t_W - t_L)}{L C_{SL}}$$

$$t_W = \frac{\left\{ C_{AG} (t_G - t_o) + \lambda_o \right\} \frac{dW}{dA} + h'_G t_G + h_L t_L}{h_L + h'_G}$$

Fig. 3-12 - Summary of the Condenser Model

and

$$\frac{dW}{dA} = k_Y (Y - Y^*) \quad (3.13)$$

An energy balance for the gas phase gives

$$-\frac{dt_G}{dA} = \frac{h'_G}{G C_{SG}} (t_G - t_w) \quad (3.14)$$

where

$$h'_G = \frac{-G C_{AG} \frac{dY}{dA}}{1 - \exp\left[G C_{AG} \frac{dY}{dA} / h_G\right]} \quad (3.15)$$

h'_G is the vapor phase heat transfer coefficient, adjusted for the mass transfer effect.

Similarly, a differential equation for the desiccant temperature change can be obtained from a liquid phase energy balance:

$$-\frac{dt_L}{dA} = \frac{h_L}{L C_{sL}} (t_w - t_L) \quad (3.16)$$

Now, from an overall energy balance,

$$L C_{sL} \frac{dt_L}{dA} = G C_{SG} \frac{dt_G}{dA} + G \lambda_o \frac{dY}{dA} \quad (3.17)$$

an expression for the condensate temperature, t_w can be obtained:

$$t_w = \frac{C_{AG} (t_G - t_o) + \lambda_o \frac{dW}{dA} + h'_G t_G + h_L t_L}{h_L + h'_G} \quad (3.18)$$

These sets of differential equations were solved using a similar method to that used for the packed column.

d. Simulation of Operation

Models for the condenser, packed column and the dryer were interactively combined to simulate the operation of the process system.

In the simulation of the regeneration operation, an initial set of conditions at the bottom of the column is assumed at a given time and the quasi-steady steady conditions at the top of the column are computed using the iteration scheme described previously. Then using these conditions as input to the condenser, the bottom conditions for the condenser were computed and compared with the initially assumed conditions for the column. This iteration procedure is continued until the difference falls within an acceptable error range.

A similar procedure is also used for the closed cycle operating mode. These simulation models are presented in Figs. 3-13 and 3-14.

3.2.2 Design Parametrics

Figure 3-15 shows the effect of air flow rate to the drying rate for a pilot scale batch dryer (50 bu of peanuts). Forty percent relative humidity at 90 F is assumed as the condition of air at the inlet to the bin. It is interesting to note that the constant drying rate period is not observed at air flow rates greater than 20 cfm/bu*. The drying rate is initially higher at higher flow rate and becomes lower than that at lower flow rate after about 11 hours of drying; 20 cfm/bu gives a constant drying period of approximately seven hours. This means that the air at the top of the bin is saturated (100% relative humidity) and that the drying front is within the crop bed for this period.

During the open cycle drying operation the moist air is expended to the atmosphere and it is therefore advantageous to have the air at saturated conditions for the maximum utilization of the thermal energy supplied to the air. It is evident from the figure that the optimum air flow rate is approximately 20 cfm/bu. Even lower air flow rate may also be used for the open cycle

* Cubic feet per minute, per bushel.

Fig.3-13 - Simulation Model for Regeneration/Open Cycle Operation

ABSORPTION COLUMN

Fig. 3-14 - Simulation Model for Absorption/
Closed Cycle Operation

Fig.3-15 - Effect of Air Flow Rate on Drying Rate (Depth of Bin: 4 ft, 50 bu Peanuts)

drying, however, this will require a longer drying time to achieve the desired final moisture content.

The regeneration operation must be controlled such that the available energy to the L/G heat exchanger is matched the amount of energy required to heat the ambient air. The energy requirement is a function of the ambient temperature and humidity and, therefore, appropriate controls are needed. This will be discussed in Section 3.3.

Figure 3-16 presents the results of a parametric study for the stripping column. The flow rate of desiccant used in the analysis is 1500 lb/hr solution at 240 F. A combination of the column diameter and the packed height may be selected from the figure for the required level of performance. For example, a 1 ft diameter, packed 5 ft high, will allow the required performance level to be attained. A specific selection, however, should be based on the economics of the column. It is noted that the performance level is limited by the equilibrium characteristic of the separation process. That is, it is not always possible to attain a higher performance by simply increasing the packed height. Either higher regeneration temperature or higher desiccant flow rate may be necessary to increase the regeneration rate.

A similar design parametric is presented in Fig. 3-17 for the condenser. Again, the selection should be based on economics. It is noted that the performance is higher for smaller tube diameters and for longer tube lengths. However, care must be taken to avoid blocking the air passage due to flooding of condensate when a smaller and/or longer tube size is used. Blocking of the air passage by the condensate may be minimized by using a certain fluted tube. This will be studied in the later phase of the program.

Figure 3-18 shows the effect of the desiccant flow rate on performance of the absorption column. The column diameter used is 2 ft and the range of packed height is 3 to 4 ft. The absorption column is used to remove the moisture from the moist air from the bin during the closed cycle operation.

Fig. 3-16 - Effect of Column Diameter and Packed Height on Performance of Stripping Column

Fig. 3-17 - Effect of Condenser Geometry and Heat Transfer Area on Performance of Condenser

Fig. 3-18 - Effect of Desiccant Flow Rate and Packed Height on Performance of Absorption Column (Column Diameter = 2 ft)

As shown in Fig. 3-15, the humidity of the air is a function of the drying time. The desiccant flow rate must be controlled to achieve the desired absolute humidity at the top of the column. Constant relative humidity of air at the inlet to the bin is desirable to control the quality of the product being dried.

3.2.3 Performance Prediction

Figure 3-19 is a summary of the results obtained from a simulation of the regeneration/open cycle operation of a 50 bu, 15 point removal peanut drying system. The total amount of the condensate removed during the six hour simulation is approximately 170 lb and the corresponding desiccant concentration change is from 37 to 39.5% with 2,500 lb initial quantity of the dilute desiccant in the storage tank. The hourly removal rate of the condensate is a slightly decreasing function of regeneration time and ranges between 31 and 27 lb/hr. This is due to lower vapor pressure at higher desiccant concentration. The specific energy requirement for the regeneration operation ranges from 1,630 to 1,690 Btu/lb condensate removed.

In the open cycle drying operation, the total moisture removed from the crop is approximately 108 lb at the hourly drying rate ranging from 20 to 16 lb/hr. This is equivalent to 0.65 lb open cycle drying per lb moisture removal during regeneration. In other words, 1.65 lb of water can be removed from the crop with the energy required for 1.0 lb of condensate removal. This gives a specific energy requirement, for moisture removal in the drying, of 988 to 1,024 Btu/lb (including heat losses).

A similar simulation result is shown in Fig. 3-20 for a laboratory scale system. The laboratory system is essentially a scaled-down version of the pilot system and has a drying capacity of 1 bu per cycle. The laboratory model was built to prove the concept and to compare the test results with the predicted specific energy requirement per pound of moisture removal for this case range somewhat high (994 to 1152 Btu/lb). This is due to the high design flow for the desiccant and the inefficient heat transfer in the L/L heat

Fig. 3-19 - Simulation of Regeneration/Open Cycle Drying (Pilot System) (Flow Rate of Desiccant 1300 lb/hr at 240 F)

Fig. 3-20 - Simulation of Regeneration (Laboratory System) (Flow Rate of Desiccant: 30 lb/hr at 240 F)

exchanger used in the simulation of the system, which results in a high specific energy requirements for the regeneration (1650 to 1900 Btu/lb condensate). The influence of various operating parameters to the efficiency of the regeneration system was also investigated using the simulation model and the results are presented in Figs. 3-21 through 3-23.

Figure 3-21 shows the effect of regeneration temperature on the system efficiency for the pilot system. Both the specific energy requirement and the regeneration rate is a strong function of regeneration temperature. The energy requirement is higher at lower regeneration temperature and lower at higher temperature, and the reverse is true for the regeneration rate. The regeneration rate increases by more than 50% for a 50 deg increase in temperature. However, it should be noted that this result is for a fixed design, designed for 240 F and initial regeneration rate of 35 lb/hr. The specific energy requirement at lower temperature can be made comparable to that at higher temperature if the column is designed for the same regeneration rate.

The specific energy requirement is a slightly decreasing function of both the desiccant and the air flow rate in the regeneration loop as shown in Figs. 3-22 and 3-23. The regeneration rate can be changed as much as 30% with less than 1% change in the energy requirement by increasing the desiccant flow rate from 1,300 to 1,900 lb/hr. It is evident from these results that the control of regeneration rate should be done not by manipulating the regeneration temperature but by the desiccant flow rate to achieve higher system efficiency.

A summary of the simulation results for the closed cycle drying operation is shown in Fig. 3-24. The total amount of moisture removed from the crop during the closed cycle operation is approximately 150 lb for a 10 point removal. The corresponding concentration change in the desiccant is 40 to 37.5%. The drying rate ranges 15.5 to 8.5 lb/hr as the relative humidity of the air at the top of the bin changes from 96 to 87%.

Fig. 3-21 - Effect of Regeneration Temperature on Regeneration Rate and Energy Requirement (Desiccant Flow Rate = 1500 lb/hr, Air Flow Rate = 150 lb/hr)

Fig. 3-22 - Effect of Desiccant Flow Rate on Regeneration Rate and Specific Energy Requirement (Air Flow Rate 150 lb/hr, Regeneration Temperature 240 F)

Fig. 3-23 - Effect of Air Flow Rate on Regeneration Rate and Energy Requirement (Desiccant Flow Rate = 1500 lb/hr at 240 F)

Fig. 3-24 - Simulation of Absorption/Closed Cycle Drying (Pilot System)
(Flow Rate of Desiccant: 2000 lb/hr at 90 F)

3.3 CONTROL SYSTEM ANALYSIS

An analysis of the control system required for the baseline desiccant drying system was conducted to identify necessary control hardware and corresponding control strategy.

The process system consists basically of three unit operations: (1) the drying operation; (2) the absorption operation; and (3) the stripping operation. Because of the nature of the process system, it is operated under two basic modes — the regeneration/open cycle drying mode and the absorption/closed cycle drying mode. Although the process flow is relatively simple on the surface, the optimum control of the system requires a certain level of sophistication. This is attributable to the process being operated under transient conditions throughout the two operating modes and the desirability of an adaptive control strategy to optimize the energy input to the system.

The most important control objective is energy conservation through optimization of the system operation and efficient process management. With this objective in mind, the following criteria are developed for the selection of a control approach:

- Centralized control system to minimize operating labor and to increase control efficiency.
- High flexibility to be adaptable in implementing various control strategies.
- High level of automation for both control and data management to provide near real time control and efficient data analysis and reporting.
- High reliability to achieve reliable control with low maintenance.

The control objective can be achieved by either a conventional analog control system or a computer control system. Because of remarkable advances in

the computer and semiconductor technology in the last few years, the computer approach is now cost-competitive with the conventional analog approach which requires bulky control hardware including an individual analog controller for the individual control loops (Ref. 13). Yet the conventional system does not provide capabilities for adaptive control, process optimization, and efficient data management, to name a few, that are provided by process computers.

An initial investigation of these two approaches revealed that the computer control is the preferred option over the conventional system mainly because of the flexibility in implementing various control strategies and the increased capabilities in process optimization and data management. In addition to these advantages the computer control system also offers capability in process management by means of establishing a control hierarchy and enables the adaptive control strategy to be implemented by using control algorithms programmed through operating experience and process modeling.

A schematic diagram for a computer process control system is shown in Fig. 3-25. A microprocessor or a programmable controller may be used as the central processing unit (CPU) for a smaller scale application. The cathode ray tube (CRT) and keyboard provide various process information graphically and are used to interpret data and take control actions. The printer and the storage is used for data logging and reporting. A signal conditioning unit is provided which converts the process signals into a meaningful computer information or vice versa.

Figure 3-26 is a P&I diagram of the process system proposed for the pilot program discussed in Section 5. The pilot facility is a research tool designed for an in-depth investigation of the process system and, therefore, the computer control system has an added merit in accomplishing the proposed research program. The control strategy will be discussed in detail in the following paragraphs.

Operating Mode Control: The objective of this control loop is to provide proper sequencing of the two operating modes. The desiccant concentration

3-49

Fig. 3-25 - Schematic of Computer Aided Process Control

Legend

A Analysis, Alarm
 C Concentration, Controller
 DP Differential Pressure
 F Flow
 H Humidity
 I Insolation
 L Level
 R Recorder
 S Speed
 T Temperature
 V Voltage

Fig. 3-26 - Process and Instrumentation Diagram for the Proposed Pilot Facility

in the tank is initially dilute and the system is operated under the regeneration/open cycle drying mode. When the concentration of desiccant in the tank reaches a certain desired level then the system is automatically switched to the absorption/closed cycle drying mode. Figure 3-27 shows a schematic of the control system with the status of various process elements for the two operating modes. The triggering input signal for this control is the amount of the condensate removed during the regeneration operation. The change in the concentration of the desiccant or the total moisture removal from the crop during the open cycle drying may also be used as the triggering signal. The regeneration rate can be computed using the level signal from the condensate receiver or the desiccant tank.

Regeneration/Open Cycle Drying Control: The regeneration temperature is maintained at a desired set point by a temperature controller. The output signal from the temperature controller is used to set the rate of energy input to the heater. This control loop is locally closed and the set point is not generated by other signals. That is, the set point for the temperature controller is manually set by an operator. The reason for this is the strong dependence of the specific energy requirement with the regeneration temperature shown in Fig.3-21. The control of the regeneration rate is achieved by manipulating the desiccant flow rate. For this purpose, a desiccant flow controller is provided. The primary control element for this loop is a venturi flow meter and for the final control element is a pump speed control. The set point for the flow controller is generated by computing the thermal energy requirement for the open cycle drying which is a function of the ambient temperature and humidity, the drying rate, and the intake rate of the ambient air. The optimum control algorithm should be based on actual operating experience and/or process modeling.

The air intake rate is also controlled by a flow controller for which a blower speed controller and a flow meter are provided as the final and primary control elements, respectively. The set point for the air controller is cascaded from the air humidity measurement at the top of the bin. For an

Mode	Valves				Pumps			Dampers			Fans	
	A	B	C	D	A	B	C	A	B	C	A	B
Regeneration/ Open Cycle	○	●	○	●	○	○	●	○	○	●	○	○
Absorption/ Closed Cycle	●	○	●	○	○	●	○	●	●	○	○	●

○ Open or ON
● Closed or OFF

Fig. 3-27 - Schematic of Operating Mode Control

energy efficient operation it is desirable to have the air leaving the system saturated throughout the open cycle operation. However, the temperature of the air at the bottom of the bin is a constraint in generating the set point for the air flow controller in order to maintain the drying temperature in the desired safe range. For this reason the output from the air temperature controller is used as an override signal in generating the set point for the air flow controller.

Figure 3-28 illustrates the need for an adaptive control strategy for the open cycle drying by means of a psychromatic chart. When the ambient condition is within the region A the normal open cycle mode (A) is adequate. That is, the desired relative humidity and the drying temperature can be achieved by simply heating the air stream. In the illustration it is assumed that the desired relative humidity is 35% and that the range of the drying temperature is 90 to 110 F. Region B represents rather dry and cool ambient air condition which is more likely in the fall. In this case recycling of the humid air from the top of the bin (B) is desirable to adjust both the humidity and the drying temperature, although it could be conducted under mode (A) at lower drying temperatures. The pure temperature effect on the drying rate is generally not significant as compared to that of relative humidity.

When the weather is hot and humid and the ambient condition lies within region (C), the desired relative humidity cannot be achieved without overheating the drying air. To remain in the safe drying temperature range, dehumidification of the ambient air is required before it is delivered to the drying bin. The absorption column may be used for this purpose. The used dilute desiccant in the previous closed cycle drying operation has sufficient potential for this dehumidification due to high absolute humidity of the intake ambient air. The normal operating range of the column for the closed cycle mode is 0.01 to 0.016 lb H_2O /lb dry air while the same for operating mode (C) ranges from 0.019 to 0.03 lb H_2O /lb dry air. The use of the absorption column could be avoided by conducting the regeneration operation during nighttime. It is likely to find the ambient air in the region A during the night when the daytime ambient air is within region C. However, the use of solar energy in

Fig. 3-28 - Adaptive Control Strategy for Open Cycle Drying

the regeneration operation for this case requires thermal storage. The operating mode (C) could be added in the operating mode control discussed in the previous section.

Absorption/Closed Cycle Drying Control: The manipulated variables for this operating mode include the desiccant flow rate and the air flow rate. The controlled variables are the temperature and the humidity of the air stream to the bin, and the drying rate. The set point for the absolute humidity controller at the outlet of the column is cascaded from the temperature controller and the output of the humidity controller is used as a set point generating signal for the desiccant flow rate. The drying rate is controlled by the air flow controller using the set point generated by the humidity signal from the top of the bin. An overall optimization program would also be used to supervise all the control functions. This, of course, will be developed in the later phase of the program utilizing actual operating experience and/or process modeling.

Environmental and Safety Control Strategy: Alarms are provided to warn the operator of hazardous or unsafe operating conditions. When the computer detects an alarm situation it will automatically take necessary steps to correct the situation in accordance with preprogrammed instructions.

For environmental protection, a lithium chloride monitoring system and a dust removal system are provided. Although lithium chloride is relatively nontoxic it is desirable to prevent contamination by carry over from the absorption column. An automated analysis device for either the lithium ion or the chloride ion would be used. The laboratory test results presented in Section 4 proved that a properly designed demister is adequate to prevent the contamination. Hence, the concentration of the lithium chloride in the air from the column will be extremely small, if there is any at all. In the event that an adequate monitoring device is not available "off-the-shelf," a manual analysis method will be used. The result of the monitoring will be used in deciding whether or not a secondary separation device should be installed.

A filter bed is provided for removing the dust, bees' wing, etc., from the air and the differential pressure across the filter bed will be continuously monitored to determine the need for replacement or cleaning the filter. If the use of a filter bed is not adequate due to excessive dusting, alternative ways will be considered for installing an electrostatic precipitator or even a cyclone separator (Ref. 14). The amount of dust from the crop depends on the type of crop and, therefore, field test experience is desirable in determining a specific approach for the dust control system.

3.4 SOLAR COLLECTOR ANALYSIS

An analysis was made to determine the best method for integrating a solar heat source with the desiccant drying system and to predict the performance of candidate solar collectors under various solar insolation conditions. The analysis was done primarily for the planned mobile pilot drying facility in which there will be practical constraints on the size and configuration of the solar collector array. The results of the analysis also provided useful insight into utilizing solar energy for a commercial-scale fixed-site desiccant dryer installation

The pilot drying system will have a total energy input requirement of approximately 324,000 Btu for a six-hour (nominal) regeneration period. This is based on a desiccant temperature rise which averages 56 F, with a final temperature of 240 F, and includes a 20% allowance for heat losses. The average flow rate is 1500 to 2000 lb/hr. The external input heat is to be provided in two stages, by a solar heat stage, followed by a conventional heating stage. The area available for the solar collector is approximately 10 x 28 ft or 280 ft².

Based on the additional cost and complexity associated with the use of a separate heat transport loop for the collector, it was determined that the desiccant should flow directly through the collector. Based on the area constraint for the collector it was determined that the full energy input could not

be provided with 280 ft^2 of collector area. For this reason the collector must be considered as a preheating or "assist stage" of heating. Two candidate collectors, one concentrating and one flat plate, were selected and a study was made to predict the performance of each, and to compare their potential for use with the mobile pilot system, and to some degree, their applicability to a commercial size desiccant drying installation. The performance calculations were made considering both clear day and actual insolation conditions as well as various tilt angles. Most of the calculation (time dependent simulations) were made using a performance prediction computer program developed by Lockheed-Huntsville for application to a variety of solar energy system simulation requirements.

The high temperatures required by the regeneration process seems to demand that a concentrating collector of some type be used in order to operate at a reasonable collector efficiency. However, the spacing between concentrators (tracking) is a major consideration to eliminate shading of one collector by another as they track the sun across the sky. A comparison of collector specifications shows that approximately 12 flat plate collectors (195 ft^2) or 14 concentrating collectors (135.8 ft^2 with 2:1 packing ratio) can be utilized within the allowable area. Furthermore, they are of comparable capital cost as total systems (not as cost per square foot). It should be noted that the packing ratio of 2:1 was determined by considering that tracking is done only for the 6 hours period about solar noon.

Performance Calculations: Using the ASHRAE clear day insolation model (Ref. 15) it was determined that the entire load could not be handled by solar energy. The flat plate collectors could handle approximately 44% of the load (144,200 Btu) on an average clear day over the six-hour period. The concentrator collectors also carried approximately 44% of the load (143,900 Btu) on a similar day. A tilt angle of 25 deg from horizontal was used for calculation along with clear day insolation data for 21 September. The collectors (in both cases) were divided into two banks of six collectors in parallel with the two banks in series. The two banks of collectors will

be operating at different efficiencies since the inlet temperature will be greater on the second bank than the first. The clear day calculations revealed that the ΔT across the first bank of flat plates was about 13 F, while the ΔT across the second bank was approximately 12 F. This is equivalent to efficiencies of 47 and 44%, respectively. The efficiency of the concentrating collectors was 62% (13 F) and 60% (12 F) for the first and second banks. From these data it is not evident as to the choice of collectors unless one considers the impact of non-clear days on each collector's performance.

A computer simulation of collector performance was performed utilizing three months of actual weather data from Huntsville (August, September and October). The collectors (both flat plate and concentrator) were varied from tilts of 20 deg to 50 deg from the horizontal. At the optimum angle for August, the flat plate collector collects approximately 11% more energy than the concentrator over the month during the 6 hours collection period about solar noon (see Fig. 3-29). During September and October, the flat plate collector captured 34 and 53% more energy than the concentrator at the respective optimum tilt angle for each month. The difference in energy collected by the concentrating collector (dashed lines in Fig. 3-29) and the flat plate collector (solid lines) is due largely to the diffuse component of insolation throughout the month. A comparison with calculations made using 20-year average data seems to support the theory that August was fairly representative of a good month. If August is taken as a clear month, it is evident that the 195 ft² of flat plate collector captures more energy than the 135.8 ft² of concentrating collector. Certainly if September and October are considered, the concentration is obviously less effective than the flat plate collector for months which have many overcast days. Of course, this is because overall cloudiness produces low beam component radiation and has relatively little effect on the diffuse component. On the average, the diffuse component makes up approximately 10 to 30% of the total radiation on a clear day, and between 50 and 100% of overcast days. The simulation showed that even though the concentrator operates at a higher efficiency over the three-month period, it has less available energy to collect. For the three months simulated, the flat plate supplied 26% of the load compared to only 20% for the concentrator.

Fig.3-29 - Collector Performance Simulation

Summary: In many applications, especially where high temperatures are necessary and there is not a high incidence of cloudy weather, the concentrating collector has the advantage over the flat plate collector systems. Specifically, the higher efficiency results in less collector area required to collect a given amount of energy. This approach has good potential for a full-scale desiccant crop dryer at a fixed location. However, for a mobile system where the total area is limited by practicality, the flat plate collector is a better choice. The limited area, coupled with elimination of the concentrator's main advantage of achieving low incidence angles during the early morning and late afternoon hours, is the primary disadvantage of the utilization of a concentrating collector system for a mobile desiccant crop dryer. In some applications, it may well be necessary to regenerate the desiccant over the entire 24-hr period or at least the daylight period, which could favor a tracking system.

This analysis has been based on existing available collectors. Future work should consider the use of new generation concentrating collectors such as the CPC (compound parabolic collector) under development by Argonne National Laboratories. This collector which requires a minimum of tracking, appears suitable for many process heat requirements where temperatures exceed 200 F.

3.5 SYSTEM END USES AND ECONOMICS

Analysis of the technical and economic characteristics of the regenerated desiccant drying system has shown that its two predominant characteristics are its high efficiency and its high capital cost, both as compared to conventional heated-air drying systems. When solar collectors are used as a primary thermal input, the requirement for fossil fuel is considerably reduced although the system cost is increased. Because of the present capital-intensive nature of the system it is important to initially use it primarily for application where it is operated as much of the year as is possible. Also, economy-of-scale considerations are such that the system capacity should be as large as is practical. For this reason, the most promising

agricultural application appears to be utilization at a large central processing facility such as at a grain elevator complex. Although on-farm use should not be ruled out since future costs will decrease with mass production, and fuel savings will become more significant, it is evident that the system should be used for large multi-crop farms where it can be operated for at least six to eight weeks of the year. The central processing application would include such operations as the drying and processing of soybeans, which is an application in which the drying operation could be totally closed-cycle, with the available heat from the regeneration loop used for some auxiliary thermal requirement.

For drying specific crops, it appears that the regenerated desiccant system is particularly suited to more delicate crops such as rice, peanuts, oats, barley, soybeans and seed crops that require lower temperatures.

Table 3-5 lists several potential end uses for the regenerated desiccant drying concept.

The use of solar energy to operate the drying system is seen as an option for obtaining further fossil fuel savings over the 40 to 50% saving achievable purely through the increased drying efficiency. The use of solar energy, which like the drying system itself is capital-intensive, must therefore be justified on a separate basis. A situation favorable to the use of solar energy for short-duration drying, and one which has been previously recognized by ERDA (Ref. 16) is that of a multi-use collector array.* Therefore, if the array can provide heat to a desiccant drying process as well as to other uses such as building heating and cooling, its capital cost chargeable to the drying process can be prorated, giving more favorable economics with respect to the drying process.

*Reference 16 states that "ERDA will examine numerous approaches to multiple-use solar collectors (drying plus other farm uses) for both large and small farms." Reference 16 also describes the ERDA/New Mexico Solar Irrigation project where the collector system, when not operating the irrigation pump "can deliver 10,000,000 Btu/day for other uses," including crop drying, greenhouse heating, fish farming, and farmhouse heating.

Table 3-5

POTENTIAL END USES FOR REGENERATED DESICCANT DRYING CONCEPT

Agricultural
Crop Drying
On the Farm
At Grain Elevators (Central Processing)
Industry
Chemical
Primary Metals and Mining
Paper
Stone, Clay, Glass, Concrete
Food Processing
Textiles
Lumber Drying
Pharmaceutical
Plastics
Environmental
Biomass Conversion
Coal Processing

Presented in Appendix C is an economic analysis which compares the cost of desiccant drying with conventional drying and addresses the economic effects of using solar energy. It was based on the requirement to dry 100 to 200 bu/hr of seed corn on a continuous basis, with a water removal rate of 600 lb of water per hour. The results should be generally applicable to larger systems up to, perhaps, 6000 lb of water per hour, which is representative of a centralized drying operation. The results of this analysis showed clearly that the "payback period" or time to recover the additional cost of a regenerated desiccant system is a strong function of the use factor, e.g., number of days per year of operation. This is true since the additional capital cost must

be paid for by fuel savings. For example, using accelerated depreciation and 10% annual fuel cost evaluation, the payback period is less than seven years if the system is used for at least 60 days per year. If solar collectors are used in the same case to provide 75% of the energy required by the dryer the payback period is close to 10 years. However, if the dryer is used for up to 180 days, the corresponding payback periods are two years for fossil fuel and five years for solar. Since future applications of the regenerated desiccant dryer will be determined largely by economic considerations, more information is needed to firmly identify specific applications and establish economic competitiveness. Much of this is expected to be obtained during the pilot facility program described in Section 5. It will also be desirable to evaluate potential industrial applications as well as agricultural drying since year-around operation will provide favorable economics.

3.6 STEPS TO COMMERCIALIZATION

Commercial application of the regenerated desiccant dryer should be possible in three to five years, based on an orderly program of system development and evaluation. Figure 3-30 depicts a logical program structure leading to commercial applications. The first two program steps have now been completed, providing a firm basis for proceeding with a parallel program of pilot-plant testing and R&D/optimization activities. The first pilot-scale activity is described in Section 5. The second pilot-scale activity will be conducted only if needed to gain additional operational and performance data on an optimized basis. The parallel R&D activity will focus on reducing system cost and improving performance. As appropriate, improvements will be incorporated into the pilot system(s) and, conversely, information gained from pilot system test and evaluation will be input to the R&D activities. The final step prior to commercialization will be to conduct a commercial-scale demonstration reflecting user requirements and involving industrial equipment manufacturers.

Fig. 3-30 - Regenerated Desiccant Crop Drying Program Overview

Section 4.

LABORATORY DEMONSTRATION SYSTEM TEST AND EVALUATION

Based on the process design studies described in Section 3, a bench-scale laboratory version of the regenerated desiccant system was designed, built, and subjected to experimental test and evaluation. The major purpose of this effort was to provide laboratory verification of the technical feasibility of the system and to demonstrate its performance characteristics and, in particular, its energy-efficiency in drying a test crop. Other objectives were to gain information needed for defining a pilot-scale system, and to verify the performance of the mathematical models described in Section 3.

The design approach was as follows:

1. Provide for drying a 1 bu test crop (1.25 cu ft of raw unshelled peanuts) using lithium chloride desiccant.
2. Utilize an 18 hr drying cycle. Starting with dilute desiccant and a moist crop, regenerate the desiccant for 6 hrs, using the remaining thermal energy for open-cycle drying. Complete the drying cycle during 12 hrs of closed-cycle operation, in which the remaining water in the crop is absorbed into the desiccant.
3. Use electrical heat to simulate solar/fossil fuel heating of the desiccant.
4. Provide sufficient instrumentation to assess the basic performance of the system and compare its performance with analytical predictions.

4.1 SYSTEM DESCRIPTION.

Figure 4-1 is a flow schematic of the experimental system, and Fig. 4-2 is a photograph of the completed system. Table 4-1 gives principal design parameters. Table 4-2 presents the predicted performance, using the mathematical models described in Section 3.

Fig.4-1 - Laboratory Demonstration System Schematic

Fig. 4-2 - Photograph of Laboratory Version of Regenerative Desiccant Crop Drying System

Table 4-1
DESIGN PARAMETERS FOR LABORATORY
DEMONSTRATION SYSTEM

Drying Capability	1 bu in 18 hrs
Air Inlet to Crop Bin:	
Temp., F	90
R.H., %	40
Flow, cfm	20
Absorption Column Packing:	
Size, Diameter x Height	5 x 24 in.
Type Packing	1 in. o.d. Raschig Rings
Desiccant Flow to Absorption Column:	
Rate, lb/hr	45
Temp., F	90
Conc. Init./Final, %	40/37
Desiccant Flow to Regeneration Column:	
Rate, lb/hr	30
Temp., F	240
Condenser Inlet Temp., F	90
Regeneration Column Packing:	
Size, Diameter x Height	3 in. x 36 in.
Type Packing	0.28 in. o.d. Raschig Rings
Desiccant Storage, lb	52

Table 4-2
PREDICTED PERFORMANCE FOR LABORATORY SYSTEM

Regeneration Loop [*]	
● Condenser:	
Desiccant Outlet Temp., F	137.5
Air Outlet Temp., F	113
H ₂ O Condensation Rate, lb/hr	0.708
● Regeneration Column:	
Desiccant Outlet Temp., F	181
● Desiccant Temp., HX-1 to:	
Open Cycle Drying	142.5
● Energy Available for Open Cycle Drying	
Btu/hr	1027
Btu/cycle	6160
● Energy Input to Regeneration Loop ^{**}	
Btu/hr	1248
Btu/cycle	7490
Absorption Loop (Closed Cycle)	
● Crop Bin	
Exit Temp., F	73
Exit Humidity, %	90
Moisture Removal Rate, lb/hr	0.35
● Absorption Column	
Desiccant Outlet Temp., F	85
Dry Air Outlet Temp.	85
Dry Air Outlet, R.H., %	
Total Water Removed from Crop	
in 18 hrs, lbs	7.07
Specific Energy Input ^{***}	
Btu/lb H ₂ O Removed	1062

^{*} 6 hr averages; ^{**} Heat losses not included; ^{***} Calculated from 7490 Btu/7.07 lb H₂O.

The following paragraphs describe the design and operation of the system, followed by the results of the experimental testing and performance evaluation.

4.1.1 General Design Features

The laboratory system, except for the desiccant tank and power supplies, is mounted on a rigid Formica-covered base frame. The system consists of two independent subsections termed the regeneration loop and the drying (absorption) loop, and includes the desiccant storage tank and feed pump. Approximate overall dimensions are 6 x 3 x 5 ft high.

4.1.2 Absorption Loop and Desiccant Storage

The absorption (drying) loop consists of the crop bin, absorption column, air blower, air/desiccant heat exchanger, air ducting, desiccant storage tank, desiccant feed pump/piping, and instrumentation.

The crop bin is constructed of plexiglass material and is approximately 12 in. in diameter by 42 in. high. Air flow is upward, with the crop resting on a perforated metal support plate. The bin is removable from the system.

The air ducting is 3 in. i.d. PVC pipe. Nominal air velocity is 6.7 ft/sec. The blower is a squirrel cage unit with a 24 Vdc motor and permits variable speed operation with air flow up to 40 cfm for closed cycle drying. For open cycle drying, air is drawn in upstream of the blower and discharged from the top plenum of the crop bin.

The absorption column is fabricated from 6 in. o.d. PVC pipe and (refer to Fig. 4-1 schematic) has a 3 in. moist air inlet at the bottom and a 3 in. dry air outlet at the top. The packing consists of a 24 in. height of 1 in. o.d. Raschig rings cut from PVC pipe. The packing is arranged randomly (dumped) and is supported on a perforated plastic plate giving a 47% flow area.

The inlet desiccant flow is uniformly distributed on the top of the packing and flows down countercurrent to the upward air flow. The flow distribution provides a low velocity uniform flow of desiccant through thirty-two 0.0316 in. diameter holes. Just above the distributor is the demistor which was installed to ensure that no air-entrained liquid can pass out of the column. It consists of a 3 in. height of packing rings resting on a wire-grid support plate. The bottom of the column provides a 4 in. liquid sump and prevents air from entering the desiccant outlet. A level gage provides visual monitoring of the liquid level.

The air/desiccant heat exchanger (HX-2) uses a standard fin/tube core and is mounted integral with the air blower. The unit is used for fine control of air temperature during closed cycle drying and to heat ambient air during open cycle drying when hot desiccant is available from the regeneration loop.

The desiccant feed pump supplies desiccant to both the absorber column and to the regeneration column. It is a self-priming variable speed gear-type pump with Teflon gears and 316 Stainless Steel body and shaft. Maximum flow is 1.5 gpm.

The desiccant storage tank is a 10 gal cylindrical vessel of Nalgene plastic. Desiccant is withdrawn through a Tygon suction line with filter. Normal desiccant volume is 5.2 gal. An additional identical tank is provided for a two-tank operating mode.

Drying Loop Control: Control and regulation of the drying loop is straightforward and consists only of maintaining constant flow of air and desiccant and maintaining the desiccant level with the absorption column. The latter is accomplished by permitting gravity flow of desiccant through the heat exchanger and out the top of the heat exchanger into a 3 in. vented overflow chamber which drains to the storage tank. Air flow is controlled by varying the input voltage to the blower. Desiccant flow is controlled by setting the voltage to the pump.

Instrumentation and Monitoring: Thermocouples are provided for measuring ΔT across the crop bin, ΔT across the absorption column and the desiccant inlet temperature. Laboratory-type (0.5% accuracy) dial thermometers are also used for measuring all principal air and desiccant temperatures. For measurement of air flow rate, a calibrated sharp-edge orifice is installed in the air ducting. The orifice Δp is measured with an alcohol-filled U-tube manometer which is also used to measure Δp across the crop bin and absorption column. Desiccant flow rate is monitored with a Gilmont ball-type 2% accuracy flowmeter. Certified hygrometers with 2% accuracy are used to determine the relative humidity of the air entering and leaving the crop bin (also the relative humidity of the air entering the absorption column). With accompanying temperatures, the absolute air humidity can also be determined. For measuring desiccant concentration, a direct reading Fisher hydrometer is used. Specific gravity range is 1.200 to 1.400. With the specific gravity and temperature known, the lithium chloride concentration is read from a conversion chart which was prepared for this purpose.

4.1.3 Regeneration Loop

The regeneration loop consists of the regeneration column, the condenser, the L/L heat exchanger (HX-1), the heat source assembly with thermostat and power controller, a circulating blower, a desiccant pump, and instrumentation. Desiccant is supplied to the regeneration loop by the same feed pump and storage tank used with the drying loop. In operation, the desiccant is first pumped to the condenser where it receives heat from condensing vapor in the moist air which exists from the top of the regeneration column. The desiccant stream then flows through HX-1 where it is further preheated in counter-flow fashion by the hot desiccant stream from the bottom of the column. It is then heated electrically and introduced into the regeneration column where it gives up water vapor to the dry air stream from the condenser and becomes more concentrated. It then flows through HX-1 and over to the drying loop heat exchanger, HX-2, and is cooled to its original temperature while giving up heat for open cycle (thermal) drying of the crop. Desiccant circulation continues in this fashion until the desired amount of water has been removed from the desiccant (and the desiccant is ready to be used in the drying loop for closed cycle crop drying).

The regeneration column is fabricated from 2.9 in. i.d. copper tubing and contains 36 in. of packing consisting of 0.28 in. o.d. x .28 in. long glass Raschig rings. A 3 in. thickness of this packing is also used as a demister, located just above the desiccant distributor tube. The air inlet and outlet ports are 1 in. i.d. and the desiccant inlet and outlet ports are 0.5 in. diameter. The column is insulated with 2 in. thick calcium silicate material for minimum heat loss. Overall column height is approximately 54 in.

The condenser is a conventional shell/tube configuration with the desiccant flowing upward in the shell and the air/water-vapor mixture and condensate flowing downward through 27 copper tubes of 0.375 in. o.d. soldered at the ends. The total gas-side heat transfer surface area is approximately 3.3 sq ft. The air inlet/outlet ports are 1 in. i.d. and the desiccant ports are 0.25 in. NPT. Condensate water drains from the bottom end of the condenser shell. The condenser assembly is also insulated with 2 in. of calcium silicate material.

The blower, which circulates air flow between the regeneration column and the condenser, is a small (2 in. impeller) squirrel cage unit and is driven by variable speed ac motor. The motor is thermally isolated from the blower by the use of a 12 in. long stainless steel shaft. The motor is energized by a Variac unit which provides variable speed operation.

The L/L heat exchanger (HX-1) is a counter flow arrangement consisting of 16 ft of 0.25 in. o.d. copper tubing within 0.375 in. i.d. Tygon tubing and formed into a 5 in. diameter coil. The total heat transfer area is 1.05 ft². The coil is mounted within a 6 x 6 in. plastic enclosure and surrounded by fiberglass insulation. Hot desiccant from the bottom of regeneration column flows through the annular space between the copper and Tygon tubing.

The desiccant pump, used to pump hot desiccant to the drying loop heat exchanger, is a small oscillating type pump of 0.1 gpm capacity driven by 60 Hz voltage pulses. It is powered by a standard Variac unit.

The electrical heater assembly consists of a Chromalox 750 W copper sheathed immersion heater mounted in a 1.25 in. diameter copper enclosure as shown in Fig.4-3. The heater element is wrapped with 0.060 in. o.d. copper wire to increase the heat transfer area and minimize vapor bubble formation. The heater also houses a thermostat capillary bulb as part of the over-temperature protective circuit. The heater is powered by an SCR voltage device. Insulation is 1 in. fiberglass covered with aluminum foil.

The desiccant piping (both loops) is primarily 0.25 in. o.d. copper tubing with brass compression fittings; 0.25 in. and 0.50 in. threaded brass pipe and fittings are also used in the system. For low temperature, low pressure piping, CPVC plastic pipe and Tygon clear plastic tubing are used.

Regeneration Loop Control: Control of the regeneration process over the nominal 6 hr period consists of regulating the desiccant feed flow rate, the desiccant return flow rate, the blower speed, and the desiccant inlet temperature to the regeneration column (nominal 240 F). As with the drying loop, the desiccant flow and air flow are controlled by setting input voltages. The temperature of the desiccant entering the regeneration column is controlled by adjusting the power input to the immersion heater by adjusting the SCR controller output voltage. To guard against an accidental over-temperature condition, a double pole adjustable thermostatic relay is provided that limits the desiccant temperature in the heater assembly.

Instrumentation and Monitoring: Regeneration loop principal temperatures are monitored with thermocouples and with direct readout dial thermometers. As with the drying loop, desiccant flow rate is measured with a ball-type flowmeter and checked periodically by direct volumetric measurement. Water outflow rate from the condenser is made with direct volumetric measurements at timed intervals. External heat input to the desiccant is determined by measuring the ΔT across the heater unit and determining the net heat addition (enthalpy change) from

$$Q = \Delta H = \dot{m} C_p \Delta T$$

Fig.4-3 - Schematic of Desiccant Heater Assembly

where $\dot{m}$ is the desiccant flow rate, and C_p is the desiccant specific heat. The electrical input can also be measured but will reflect heat losses from the heater assembly and adjacent lines and fittings. Since this loss is difficult to determine, the $Q = \Delta H$ method, which gives the net heat added to the desiccant, is used. The concentration of the desiccant in the storage tank, which increases slowly with time is measured with a hydrometer as was previously described for the drying loop.

4.2 EXPERIMENTAL TESTING AND ANALYSIS

Fabrication and assembly of the absorption (drying) loop was essentially completed in early November 1976, and three preliminary closed cycle drying tests were made. The regeneration loop was completed in early December, and the first steady-state instrumented test was made on 7 December 1976. Good results were obtained. In early January the electrical heater installation was modified to minimize measurement uncertainties due to the effects of vapor formation (boiling) in the heater unit. Following additional performance and checkout tests, a complete drying cycle test of 18 hrs duration was conducted and served as the principal verification of the technical feasibility of the regenerated desiccant drying concept. The total operating time for the drying loop was approximately 60 hrs. Total operating time for the regeneration loop was roughly 30 hrs. For the experimental program, the test crop used was one bushel (1.25 ft^3) of raw unshelled peanuts, with moisture added as necessary.

The following paragraphs will describe the results of the experimental tests, system operating characteristics, and general observations made. Principal emphasis is placed on the results and evaluation of the 18 hr full cycle test which was compared with analytical performance predictions made using the mathematical models described in Section 3.

4.2.1 Absorption Loop

Since it was not practical to use an actual fresh harvested crop for the various drying tests that were made, all drying tests were conducted using raw unshelled peanuts, with distilled water added as necessary, for each test, to obtain the desired moisture content by weight. This proved to be a convenient technique and it is believed that it provided a reasonably accurate simulation of a fresh crop. Although drying rates could differ somewhat, the overall system thermal efficiency characteristics are not dependent upon drying rates.

For the absorption loop, the major objective was to demonstrate and study the closed cycle process of removing moisture from a crop (or other commodity) by taking moist air flowing from the top of the bin, passing it through an absorption column and delivering dry air to the bin to absorb moisture from the crop and complete the cycle. The net result of this process is that in time the total water removed is deposited in the tank of desiccant. This was demonstrated several times prior to the overall test, and no problems were encountered. When the process is started (by initiating desiccant and air circulation), evaporative cooling of the crop begins and the mass begins to cool gradually. At the same time the water vapor being absorbed by the desiccant stream flowing over the packing rings of the column causes the desiccant to heat due to the heat of solution and the latent heat of condensation. After about 15 to 30 min the system reaches a pseudo steady-state in which there is a substantial ΔT of the air flowing through the crop bin as well as through the column. Figure 4-4 shows this typical starting transient and also shows that as the drying proceeds the ΔT gradually decreases. The reason for the desiccant outlet temperature decrease is the initial cooling effect of the air entering the column. It was also found that the relative humidity of the bin inlet air stays relatively constant while the humidity of the outlet air gradually decreases.

During air flow at the nominal rate of 20 scfm, the pressure drops, in inches of water, for the crop bin and absorption column were 0.1 and 0.2 in. of water, respectively.

Fig.4-4 - Typical Drying Characteristics During Closed Cycle Operation

During the drying loop tests, frequent visual checks were made to determine if any desiccant solution droplets were being swept out of the top of the absorption column. No evidence was found even after increasing the air flow rate to near 40 scfm. This was not unexpected since the desiccant impinges on the packing in low velocity streams of droplets and no mist is observable. At the conclusion of the test program a chemical analysis was made on a porous paper streamer in the crop bin air inlet duct. No trace of chloride was found.

During the first closed cycle drying test, which lasted for approximately 18 hrs, approximately 4.5 lb of water were removed from the wet test crop and transferred to the desiccant even though a temporary pump was being used and the desiccant flow was approximately one-half of the design value of 45 lb/hr.

This test provided a good indication that the absorption column was adequately sized. In this test the crop moisture level was reduced from approximately 22% to 10%. Further tests of the drying loop also gave satisfactory performance. An interesting observation from these tests was that the desiccant circulation rate does not have a large influence on the drying rate. Concerning the absorption column performance, it was noted that the 1 x 1 in. PVC packing rings have poor surface wetting characteristics and it was evident that the use of rings with good wetting properties would provide better performance.

Desiccant Contamination: Potential contamination sources for the desiccant were dust particles in the crop and corrosion products. Only trace amounts of dust build-up were observed in the desiccant system. Since the desiccant was exposed to copper and brass materials (as well as ambient oxygen) slight corrosion was present and some corrosion products, notably copper chloride and copper oxide, were added to the desiccant. Since these materials as well as dirt/dust particles precipitate out, they caused no problems.

4.2.2 Regeneration Loop Test

The regeneration loop, which is the portion of the system that requires external energy input, performed well in the initial checkout experiments. The condenser, intentionally oversized by 50%, performed as intended in preheating the cool inlet desiccant while condensing the moisture removed from the regeneration column by the circulating air flow. Even though there are coupling and interactive effects between the four principal components — column, condenser, heat exchanger and heat source — system temperatures were fairly stable. As described earlier, there was an initial problem associated with the electrical heating of the desiccant, in which localized boiling caused some two-phase flow of desiccant to the regeneration column. Since this introduced a degree of uncertainty in the measurement of heat input by the $Q = \Delta H$ method and added a small amount of steam directly into the column, this problem was corrected. This was accomplished by increasing the heater element surface area as well as relocating the heater assembly to provide a longer flow path and additional time for any vapor bubbles to collapse prior to entering the column.

During the first instrumented test of the regeneration loop, the system was heated to a steady state condition over a 2 hr period and was operated for 2.33 hrs. During the 2.33 hrs test period, over which the desiccant inlet temperature to the column was maintained at approximately 240 F, and the cool desiccant inlet temperature at approximately 90 F, the dependent temperatures averaged within 3 F of the predicted values. The water removal rate (from the condenser) was approximately 19% higher than predicted. The net thermal energy input to the desiccant (added by the electrical heater), was approximately 6% higher than predicted. Table 4-3 summarizes these data.

After the previously described heater modification was made, another regeneration loop test was made under identical controlled conditions. The results of this test are shown in Table 4-4. In this case, the net thermal input was also 8% higher than predicted. In this test the condenser outlet temperature was 10 F lower than in the previous 2.33 hr test, and the exit

Table 4-3
FIRST REGENERATION LOOP EXPERIMENT (2.33 HOURS)

	Predicted	Test
Average Desiccant Flow Rate (lb/hr):	30	30 $\pm$ 1
Average Desiccant Temperatures (F):		
Inlet Temperature to Column:	240	240
Inlet Temperature to Condenser:	90	90
Condenser Outlet Temperature:	138	140
Heater Inlet Temperature:	176	172
Column Outlet Temperature:	181	184
From HX-1 to Drying Loop:	143	142
Water Removal Rate (lb/hr):	0.71	0.85
Net Thermal Input Rate (Btu/hr):	1248	1325
Desiccant Conc.-Change in 2.33 hrs (%):		37.8 to 39.2

Table 4-4
REGENERATION LOOP TEST AFTER HEATER MODIFICATION

	Predicted	Test
Average Desiccant Flow Rate (lb/hr):	30	30 $\pm$ 1
Average Desiccant Temperatures (F):		
Inlet Temperature to Column:	240	238
Inlet Temperature to Condenser:	90	90
Condenser Outlet Temperature:	138	130
Heater Inlet Temperature:	176	169
Column Outlet Temperature:	181	183
From HX-1 to Drying Loop:	143	134
Water Removal Rate (lb/hr):	0.71	0.77
Net Thermal Input (Btu/hr):	1248	1345
Desiccant Concentration Change		37.7 to 38.6

temperature from HX-1 was 8 F lower. This was apparently caused by the lower condensation rate in the condenser and tends to indicate that prior to the heater modification there may have been vapor bubbles entering the regeneration column and boosting the water production rate.

The results of this test provided increased confidence in the performance of the regeneration loop and demonstrated a favorable ratio of energy input to water removal rate even though the temperatures were somewhat lower than analytically predicted.

4.2.3 18-Hour Overall System Test

The purpose of the 18-hr test was to evaluate the performance of the system in its baseline operating mode which consists of six hours of desiccant regeneration with open cycle drying, followed by 12 hrs of closed cycle drying.

a. Regeneration/Open-Cycle Operation: The initial concentration of the lithium chloride desiccant solution was 37%, the nominal value. The initial wet weight of the test crop (peanuts) was 33 lb, corresponding to a moisture level of approximately 24%. When the regeneration loop was fully heated and in a steady operating condition, the 6-hr run period was initiated and data was taken at 15-min intervals. During the regeneration period the warm desiccant flowing out of the system was channeled through the drying loop heat exchanger (HX-2) to heat air for open-cycle drying of the test crop. To simulate the intake of cool humid outside air, an atomizing humidifier was used to humidify and cool the intake of ambient (room) air. Moist air from the crop bin was discharged to ambient. During the test, the temperature of the hot desiccant entering the column was maintained as close as possible to 240 F. The temperature of the cool inlet desiccant (at the condenser inlet) was maintained at near 90 F and the desiccant flow rate was maintained at near the nominal value of 30 lb/hr. The air flow to the crop bin was set at approximately 20 scfm or 100 lb/hr.

The results of the regeneration/open-cycle test are tabulated in Table 4-4 and plotted versus time in Fig.4-5. The data in Table 4-5 are averages over the six-hour period and are compared with corresponding analytically

Table 4-5
RESULTS OF REGENERATION/OPEN CYCLE DRYING
TEST - COMPARISON WITH ANALYTICAL PREDICTIONS

Item	Test (6 hr avg.)	Predicted Value	Δ
Regeneration Column Inlet (F)	240.5	240.0	—
Desiccant Flow Rate (lb/hr)	28.4	30.0	—
Condenser Inlet (F)	87.6	90.0	—
Condenser Outlet (F)	132.4	137.5	-5.1 F
Column Outlet (F)	180.0	181.0	-1 F
Heater Inlet (F)	167.1	176.0	-8.9 F
Total Internal Preheat ΔT (F)	79.5	86.0	-6.5 F
Heater ΔT	73.3	64.0	+8.7 F
Energy Input (Btu)*	8120	7490	+8.4%
Total Water Removed from Desiccant (lb)**	4.51	4.25	+6%
Water Removal Rate (lb/hr)	0.752	0.708	+6%
Desiccant Outlet, HX-1 to Drying Loop (F)	135.0	142.5	-7.5 F
Total Energy to Open Cycle Drying (Btu)*	5250	6160	-14.8%

* Calculated from $Q = \Delta H = m C_p \Delta T$.

** Initial desiccant weight 56 lb at 37% concentration (LiCl solution).

predicted values. The test data can be seen to be in good agreement with predicted data. If there had been no heat loss from the system, the energy available to the heat exchanger (HX-1) would have been higher, and the predicted energy efficiency would probably have been exceeded. The effects of heat loss show up directly in the value of total energy available for open cycle drying, where the 5250 Btu quantity should have been approximately 6680 Btu (82% of 8120 Btu)*. This represents a loss of approximately

* Energy to open cycle is approximately 82% of input energy.

18% of the input energy of 8120 Btu. Note that during the 6-hr period, 4.51 lb of water was removed from the desiccant, and the final desiccant concentration was very near the predicted value of 40%.

During this period, the water vapor condensed within the condenser provided 4870 Btu of heat to the desiccant stream flowing to the regeneration column. This is higher than the total latent heat of the condensed water, 4650 Btu and differs by the sensible heat gain from the air flowing through the condenser (the hot moist air from the regeneration column). The 4650 Btu quantity is approximately 57% of the external heat input to the system and demonstrates the principal energy-conserving feature of the drying system.

During the 6-hr regeneration period, the test crop was being dried in an open cycle mode. The total energy input to the air was the previously mentioned 5250 Btu. The average temperature and humidity conditions of the air entering and leaving the crop bin were approximately:

Air Entering:	Temperature - 106 F
	Relative Humidity - 22%
Air Leaving:	Temperature - 66 F
	Relative Humidity - 88%

During the 6-hr period, approximately 3.5 lb of water was removed from the test crop.

Figure 4-5 graphically shows the principal test data. Note that there was some variation in the hot desiccant inlet temperature (manually-controlled) even though the average value was 240.5 F. Note that during the third hour of the test this temperature averaged about 5 F higher. This is reflected in a faster rate of water removal and an increased condenser outlet temperature during this period. The figure also shows the increase in the lithium chloride concentration of the desiccant solution, which was seen to be quite linear. The figure also shows clearly, to scale, the amount of internal preheating the desiccant receives, $\Delta T_{\text{preheat}}$, and the amount added by the heater, ΔT_{heater} ; this

Fig. 4-5 - Regeneration Loop Performance

shows that approximately one-half of the required energy input to the desiccant is supplied internally.

b. Absorption Loop/Closed Cycle Operation: Following the 6-hr regeneration period, the test crop was dried in the closed cycle mode (absorption drying) for 12 hours. Nominal initial conditions were as follows:

Desiccant Concentration	40%
Storage Temperature	90 F
Desiccant Flow Rate	45 lb/hr
Air Flow Rate	100 lb/hr (20 scfm)

Figure 4-6 shows a plot of the principal temperature and humidity variation during the 12-hour period. During this period, approximately 4.2 lb of water was removed from the test crop and added to the desiccant. Considering measurement uncertainties, this is well within 10% of the predicted water removal rate. The rate might have exceeded the predicted rate if the complete loop had been fully insulated and the air supply temperature to the bin had been higher. In Fig.4-6, analysis of the temperature drop through the crop, which is directly proportional to the water removal rate, shows that the drying rate was approximately constant through the end of seven hours, although the relative humidity of the bin exit air began decreasing. The last five hours of the test were run with a higher air flow rate, giving a slightly higher ΔT . The discontinuity shown at the end of seven hours was caused by an overnight shutdown, after which the desiccant supply was warmed to 88 F prior to starting the last five hours of drying. Note that as the end of the drying period is approached, the ΔT decreases and the exit air humidity drops.

c. Overall Performance Evaluation: The major objective of the 18-hour test was to determine the "specific energy input" or the amount of thermal energy, E , required to remove each pound of water from the crop, expressed in Btu/lb H_2O . This is determined as follows:

Fig. 4-6 - Closed Cycle Drying

Total Thermal Input (in six hours)	8120 Btu
Total Water Removed from Crop (in 18 hours)	3.5 + 4.2 = 7.7 lb
E = Specific Energy Input = $8120/7.7 = 1055 \text{ Btu/lb H}_2\text{O}$	

This is seen to virtually equal the analytically predicted value of 1062 Btu/lb. However, a more conservative calculation which avoids the uncertainty associated with weighing the test crop (scale accuracy was approximately ± 0.5 lb) and which provides a more uniform comparison with the analytical prediction method is as follows: Using the actual energy that was available for open cycle drying, 5250 Btu and using the generally accepted average specific energy input (Ref. 17) for conventional dryers, 2000 Btu thermal per pound of water removed, the water removable from the crop under average open cycle drying conditions would be $5250/2000 = 2.62$ lb. Also the water removed from the desiccant (measured to 5% accuracy), 4.51 lb, represents the actual amount which can be removed from the crop by closed cycle absorption drying. On this basis the total water removable per drying cycle is 7.13 lb and the specific energy requirement is

$$E = \frac{8120 \text{ Btu}}{7.13 \text{ lb}} = 1140 \text{ Btu/lb-H}_2\text{O}$$

This is seen to be only 7% higher* than predicted and still demonstrates a very favorable result. When considering the experimental uncertainty of the 1140 Btu/lb, based on measurement accuracies ($\pm 5\%$ for flow rate, ΔT specific heat, and weight) this number is estimated to be accurate to within 10%.

4.2.4 Conclusions

Experimental testing and analysis of the laboratory demonstration system has provided strong evidence that the regenerated desiccant crop drying concept is technically sound and can achieve the predicted energy

* On an even more conservative basis, the use of 4.2 lb instead of 4.51 lb gives 12.6%.

efficiency. In addition, the quantitative test results provided a good demonstration of the accuracy and validity of the analytical modeling techniques developed. Although the experimental system was designed for lithium chloride desiccant, the concept is applicable to other liquid desiccants and it is anticipated that similarly good agreement could be obtained between analytical and test results..

Section 5

PILOT-SCALE DESICCANT DRYING FACILITY

A program cost estimation was made for a mobile R&D pilot system of 50 bu capacity. The purpose of the facility is to permit in-depth evaluation of the regenerated desiccant drying concept. When completed, the mobile pilot facility (MPF) will be used for the following:

- Performance and design evaluation of the drying system, including the use of solar heat input
- Evaluation of drying performance for various crops (rates, quality, etc.)
- Evaluation of overall operational factors
- Use as a test bed for evaluating design improvements that may be incorporated during the program
- Demonstration of the operation and performance of the desiccant drying technique to government, university, and commercial organizations
- Development of design criteria for a commercial scale system.

The engineering definition and costing of the MPF was based on the process design study described in Section 3 for a pilot-scale regenerated desiccant system capable of drying a 50 bu crop in 18 hrs with drying air supplied at 90 F and 40% R.H. and with an average water removal rate of 15.5 lb/hr.

The basic philosophy was to define a self-contained, self-propelled mobile R&D facility complete with computer data acquisition system, control and display system, and crop handling equipment, such that it can be operated at virtually any location. Figure 5-1 shows an illustration of the MPF set up at a typical USDA experiment station for a series of grain drying tests.

Fig. 5-1 - Illustration of Mobile Pilot Facility Concept

The solar collector panels for the MPF, because of the size constraint due to roof area, are designed to provide only a portion of the input energy, with the primary energy input obtained from an electrical heat source (simulated fossil fuel burner).

The baseline design concept for the MPF is described next and is followed by a cost breakdown and program schedule.

5.1 DESCRIPTION

5.1.1 Operational Concept

Typically, the MPF will be moved to a planned location and set up as follows: The crop bin will be loaded with the desired crop or grain and the drying system prepared for operation. For solar operation the solar panels, in two sections, will be raised to the proper tilt angle. The data system will be readied for performing data acquisition, including on-line data reduction, display and storage. The drying cycle will be initiated by starting the regeneration process and regenerating the desiccant for a nominal period of six hours, while furnishing heat for open-cycle thermal drying of the test crop. Normally, this operation will be started at 9 to 10 a.m. to take advantage of available solar input. When the regeneration process is completed, the drying of the test crop will be completed during a nominal 12 hr period of closed cycle absorption drying. At the completion of the drying cycle, a report will be generated by the data system giving all pertinent performance data, including performance plots and a summary of overall drying performance.

5.1.2 Equipment Arrangement

Figure 5-2 shows the baseline equipment arrangement for the MPF. The drying system components and associated support equipment are located in the rear portion of the enclosure (truck body). Door panels can be opened or removed on three sides as shown, for access and viewing purposes. The solar collector panels are roof-mounted and lay flat on the top of the enclosure

Fig. 5-2 - Mobile Pilot Facility Conceptual Arrangement

when not in use. The forward portion of the enclosure is the data acquisition and control/display area. A grain elevator and unloader are provided as shown. Leveling jacks will also be provided.

5.1.3 Absorption Loop and Desiccant Storage

The absorption loop will consist primarily of the absorption column, crop bin, desiccant/air heat exchanger, blower, air ducting, air filter, and motorized dampers. The desiccant storage tank contains the lithium chloride solution and serves both the absorption loop and the regeneration loop. The absorption loop contains two desiccant pumps, one to pump the desiccant to the absorber and one to pump from the absorber back to the tank. The air ducting contains two filters, one to prevent dust, beeswings, etc., from entering the absorber. The other is a backup device to ensure that any desiccant mist, which might accidentally pass out of the absorber, does not enter the crop bin.

Table 5-1 lists principal design data for the absorption loop and desiccant storage.

5.1.4 Regeneration Loop

The regeneration loop primary components are the regeneration column, condenser, regenerative heat exchanger, electrical heat source unit, solar collector panels and pumps. The regeneration column, like the absorption column will be a standard industrial unit with removable packing material, fabricated primarily from fiberglass material. The condenser is a standard tube and shell single-pass unit fabricated of stainless steel, with the desiccant flowing through the shell side and the air flowing in the tubes. The regenerative heat exchanger is a standard tube and shell unit fabricated of stainless steel. The electrical heat source is a stainless steel unit with stainless-clad immersion-type heating elements. Power is obtained from a silicon-controlled rectifier (SCR) variable output power supply with 220 Vac input. The air circulation blower for the regenerator/condenser air loop is a standard variable

Table 5-1
DESIGN DATA FOR ABSORPTION LOOP AND
DESICCANT STORAGE

Bin Size, bu	50
Average Water Removal Rate, lb/hr	15.5
Absorber Packing	2 ft diam. x 4 ft high 1-1/2 in. Raschig Rings
Desiccant Flow Rate, lb/hr	2000
gpm	3.3
Air Flow Rate, cfm/bu	22
Air Inlet to Absorber	90% R. H., 73 F
Air Exit from Absorber	50% R. H., 87 F
Air Inlet to Crop Bin	40% R. H., 90 F
Heat Exchanger Area, ft ²	20
Storage Tank, Desiccant at 37%	2500 lb
Initial Desiccant Conc., %	40
Final Desiccant Conc., %	37

speed ac motor-driven centrifugal impeller unit driven by an SCR power supply. Two variable-speed centrifugal pumps are provided, one to draw desiccant from the storage tanks and pump it through the condenser, regenerative heat exchanger, solar collectors and heat source unit, and into the regenerator. The other pumps desiccant out of the regenerator through the regenerative heat exchanger and the absorption loop heat exchanger, and back to storage. Both are seal-less magnetic drive pumps with variable speed capability.

Design and performance data for the regeneration loop are given in Table 5-2. The solar collector for the regeneration loop is described in the next paragraph.

5.1.5 Solar Collector

The solar collector, which is a part of the regeneration loop, is comprised of 12 individual collector panels arranged in two segments of six panels each. Each is an available commercial design having a selectively coated copper absorber plate and two layers of cover glass. The collector is used to furnish a maximum of 44% of the required daily energy input to the regeneration loop, with the majority of the input furnished by the electrical heat source (which simulates a fossil fuel burner). The desiccant is circulated directly through the collector panels without need for a separate transport fluid and associated heat exchanger. For this reason, copper flow passages are a necessity to minimize corrosion effects. To obtain good flow velocity of the desiccant through the collector panels a parallel/series arrangement is used in which the desiccant first flows through a segment of six parallel panels then through a second segment of six panels.

The two collector segments, with a total area of 195 ft² are hinged-mounted on the roof of the vehicle. Jacking mechanisms are used to tilt the segments up to the proper operating angle.

Design data for the collector is given in Table 5-3.

Table 5-2
PRINCIPAL DESIGN DATA FOR REGENERATION LOOP

Regeneration Temperature, F	240
Desiccant Flow Rate, lb/hr	1500
gpm	2.5
Initial Concentration, %	37
Final Concentration, %	40
Water Removal Rate, Average, lb/hr	31
Open Cycle Drying:	
Air Inlet to Bin	90 F, 40% R. H.
Air Flow Rate, cfm/bu	27
Regeneration Column:	
Diameter, ft	1
Packing Height, ft	5
Packing	1 in. diam. Raschig Rings
Regenerative Heat Exchanger Heat Transfer Area, ft ²	40
Condenser Heat Transfer Area, ft ²	60
Required Heat Input Rate ² , Average, Btu/hr	45,000
kW _t	13.2

* Ambient air at 65 F, 90% R. H.

** Required from electrical heat source plus solar collector, not including losses.

Table 5-3
PRINCIPAL DESIGN DATA FOR SOLAR COLLECTOR

Number of Panels	12
Total Collection Area, ft ²	195
Total Panel Area, ft ²	217
Number of Glass Cover Plates	2
Absorber Absorptivity/Emissivity	0.98/0.30
Tilt Angle	Variable
Fraction of Regeneration Load Supplied:	
Clear Day, %	44
Average Day, %	26

5.1.6 Control/Display System

The control system includes all control elements for the complete drying system as well as the control panel located in the data acquisition area. A display panel is also provided to graphically show the operating status of the system. Individual control components will include those necessary for controlling the various flows, liquid levels, temperatures and humidity, as well as for positioning valves and dampers. Certain of the control devices will be interfaced with the data system computer, which will provide programmed control signals.

5.1.7 Data System and Instrumentation

The computerized data system will provide the following functions:

- Automatic Multi-Channel Scanning
- On-line Data Reduction
- Data Storage
- Process Control
- Information Output on Page Printer and Plotter.

The selected system is rack-mounted and will consist of a digital voltmeter, two scanners, calculator (computer), memory extender, ten channel low thermal assemblies, ten channel relay actuator assembly, character imprint printer, plotter, ASCII clock, and timing generator.

Instrumentation: The desiccant drying system instrumentation will consist of standard sensors and transducers for temperature, pressure, flow, voltage, power, humidity, and solution concentration. Outputs from this instrumentation will be routed to the scanner unit of the data system. A direct read-out moisture tester will also be provided for checking the moisture content of the crop.

5.1.8 Vehicle/Enclosure

The complete system is to be installed in a truck-mounted enclosure as shown in Fig. 5-3. The enclosure will be approximately 28 ft long by 8 ft wide by 9 ft high. Overall vehicle length will be approximately 40 ft with an overall height of 13.5 ft.

5.2 COST SUMMARY AND PROGRAM SCHEDULE

A detailed cost estimate was made for the Mobile Pilot Facility Program. The total cost of the complete 31-month program was determined to be \$550,000. This is for the design, construction and verification testing phase (Task 3) and the field R&D operation phase (Task 4). The total cost includes all material, labor, indirect costs, and fees. The material cost estimate was based largely on budgetary quotes and available pricing information. The total cost of \$550,000 is seen to be identical to the original cost estimate provided to ERDA in June 1976 and substantiates this earlier cost projection. Figure 5-3 shows the program tasks and schedule.

The following table gives the required program funding for fiscal years 1977, 1978, 1979 and 1980, based on a 1 June 1977 start date.

FUNDING REQUIREMENTS BY TASK AND FISCAL YEAR

	FY77	FY78	FY79	FY80	Total
Task 3	\$78,000	\$351,000	\$11,000	—	\$440,000
Task 4	<u>—</u>	<u>—</u>	<u>77,000</u>	<u>\$33,000</u>	<u>\$110,000</u>
	\$78,000	\$351,000	\$88,000	\$33,000	\$550,000

Fig. 5-3 - Program Tasks and Schedule for Mobile Pilot Facility Program

Section 6

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusion of the study is that the regenerated desiccant crop drying system concept is technically feasible and has the capability to achieve a drying efficiency of approximately twice that of conventional crop drying systems. When using a fossil fuel energy source, energy savings will be approximately 40 to 50%. With solar energy input, the total fossil fuel savings can be 70 to 90%. The economic feasibility of the system appears promising. As with other new energy conserving systems that are presently capital-intensive, the economic viability of the system will be dependent on future capital cost reductions, on the future price of fossil fuels, and on the specific application of the system. Regarding system applications, it was concluded that the regenerated desiccant drying system, with or without the use of solar energy, will be economically best suited for a large central processing application, where it can receive a maximum amount of use and will benefit from economy-of-scale cost considerations.

The basic study recommendations are: (1) additional R&D activities should be conducted to identify and evaluate means for achieving system cost reductions, and (2) the Mobile Pilot Facility program should be initiated.

Section 7
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Appendix A

SUMMARY OF LIQUID DESICCANT PROPERTIES

Liquid Desiccant	C _p (Btu/lb-F)	R.H. at 90 F for Sat. Solu. (%)	Useful Concen. Range (%)	Range of Regen. Temp. (F)	Chemical Stability	Heat of Dilution (Btu/lb)	Corrosion	Toxicity	\$/lb
Lithium Chloride	0.68 (70 F, 40%)	11	23-45	200-250	Stable	200	Rela. Non-Corrosive	Rela. Non-Toxic	1.26
Calcium Chloride	0.60 (70 F, 40%)	21	32-40	200-250	Sat. Solu. Solidifies Below 86 F	200	Rela. Non-Corrosive	None	0.04
Sulfuric Acid	0.4-0.6	0	35-100	250-300	Stable	200	Bad	Toxic	0.03
Glycerine (Glycerol)	0.6-0.9	0	50-100	200-250	Heat Sens. Oxidize	Low	None	None	0.50
Triethylene Glycol	0.6-0.9	0	96-100	250-300	Heat Sens.	Low	Noncorr. with In- hibitor	Toxic	0.30

Appendix B

EQUILIBRIUM MOISTURE CONTENT (EMC) DATA (% WET BASIS)*

Material	Temp	Relative Humidity (%)										Ref.
	°F	10	20	30	40	50	60	70	80	90	100	
Barley	77	4.4	7.0	8.5	9.7	10.8	12.1	13.5	15.8	19.5	26.8	(1)
Buckwheat	77	5.0	7.6	9.1	10.2	11.4	12.7	14.2	16.1	19.1	24.5	(1)
Cottonseed	77				6.9	7.8	9.1	10.1	12.9	19.6		(2)
Dry beans,	40						12.8	14.4	17.0			(3)
Michelite	50						13.8	15.3	18.0			(3)
	77	5.6	7.4	8.6	9.8	11.2	12.9	14.9	17.5 ¹			(4)
	100						12.0	14.2	17.1			(3)
	130						12.4	14.3	18.5			(3)
Dry beans,	77	6.0	7.5	8.6	9.8	11.0	12.8	15.2	18.6 ¹			(4)
red Mexican												
Dry beans,	77	5.9	7.4	8.5	9.6	10.9	12.6	15.0	18.0 ¹			(4)
great Northern												
Dry beans,	77	6.1	7.5	8.7	9.9	11.1	12.9	15.1	18.5 ¹			(4)
light red kidney												
Dry beans,	77	5.4	7.2	8.4	9.9	10.7	12.5	15.0	18.6 ¹			(4)
dark red kidney												
Dry beans,	77	6.0	7.1	8.3	9.6	11.0	12.6	15.0	18.1 ¹			(4)
flat, small white												
Dry beans,	77	6.1	7.4	8.5	9.8	11.0	12.6	15.2	18.2 ¹			(4)
pinto												
Flaxseed	77	3.3	4.9	5.6	6.1	6.8	7.9	9.3	11.4	15.2	21.4	(1)
	77				6.1	6.8	7.9	9.3	11.4	15.7		(3)
Oats	77	4.1	6.6	8.1	9.1	10.3	11.8	13.0	14.9	18.5	24.1	(1)
Peanuts,	50			5.5	6.1	7.1	8.6	9.8	11.9			(5)
pod												
Peanuts,	50			4.8	5.5	6.0	6.6	7.3	9.0			(6)
kernels												
Rice,	77	5.9	8.0	9.5	10.9	12.2	13.3	14.1	15.2	19.1		(7)
whole grain												
Rice,	100	4.9	7.0	8.4	9.8	11.1	12.3	13.3	14.8	19.1		(7)
whole grain												
Rice,	77	5.1	7.6	9.0	10.3	11.5	12.6	12.8	15.4	18.1	23.6	(1)
milled												
Rice,	80				9.2	10.4	11.7	13.2	15.0	17.1		(8)
rough	111						10.3	12.3	14.3	16.5		(8)
	32		8.2	9.9	11.1	12.3	13.3	14.5	16.6	19.2		(9)
	68		7.5	9.1	10.4	11.1	12.5	13.7	15.2	17.6		(9)
	86		7.1	8.5	10.0	10.9	11.9	13.1	14.7	17.1		(9)
	77	4.6	6.5	7.9	9.4	10.8	12.2	13.4	14.8	16.7		(10)
	73	4.9	7.3	8.7	9.8	10.9	12.4	13.5	15.9	19.0		(11)
Rye	77	5.2	7.6	8.7	9.9	10.9	12.2	13.5	15.7	20.6		(1)
Shelled corn	20				10.4	11.8	13.3	15.0	16.6			(12)
YD	32				11.0	12.5	14.0	15.8	18.0	21.8		(13)
	50	6.6	8.0	9.3	10.8	12.2	13.8	15.2	17.5	21.8		(14)
	70			7.1	8.3	9.8	11.4	13.2				(12)
	77	5.1	7.0	8.3	9.8	11.2	12.9	14.0	15.6	19.6	23.4	(12)
	90	4.9	6.6	7.7	9.3	10.8	12.4	14.0	16.2	19.3		(14)
	120				8.6	10.0	11.2	13.1	14.9			(14)
	30		6.7	9.2	10.7	12.7	14.1	17.7				(15)
	86	4.4	7.4	8.2	9.0	10.2	11.4	12.9	14.8	17.4		(16)
	60	7.5	7.8	9.0	10.3	11.3	12.4	13.9	16.3	19.8		(16)
	50				9.2	10.7	12.1	13.6	15.5			(12)
	32				10.1	11.8	13.3	15.0	16.6			(12)
	155				7.4	8.4	10.0	11.5	12.2			(14)
	160	3.9	6.2	7.6	9.1	10.4	11.9	13.9	15.2	17.9		(15)
	40	6.3	8.6	9.8	11.0	12.4	13.8	15.7	17.6	21.5		(16)
	60		4.8	6.8	8.6	10.7	12.1	13.9				(15)
	86				11.0	12.5	14.0	15.8	18.0	21.8		(13)

* From D.B. Brooker et al., "Drying Cereal Grains," 1974.

Appendix B (Concluded)

Material	Temp	Relative Humidity (%)										Ref.
	°F	10	20	30	40	50	60	70	80	90	100	
Shelled corn WD	100	4.0	6.0	7.3	8.7	9.0	11.0	12.5	14.2	16.7		(16)
	122	3.6	5.5	6.7	8.0	9.2	10.4	12.0	13.6	16.1		(16)
	140	3.0	5.0	6.0	7.0	7.9	8.8	10.3	12.1	14.6		(16)
	120				6.3	6.5	7.8	9.3	10.7			(15)
	90			5.3	6.0	6.3	10.2	12.1	13.9			(15)
Shelled corn WD	77	5.1	7.2	8.5	9.6	11.2	12.9	13.9	15.5	18.9	24.6	(1)
Shelled popcorn	77	5.6	7.4	8.5	9.6	11.0	12.2	13.1	14.2	16.4	23.0	(1)
Sorghum	30		8.2	10.1	11.2	12.3	13.5	14.5	15.8			(15)
	60		7.5	9.5	10.7	11.8	12.9	14.0	15.5			(15)
	77	4.4	7.3	8.6	9.8	11.0	12.0	13.8	15.8	18.8	21.9	(1)
	90		7.0	8.7	10.2	11.8	12.2	13.1	14.8			(15)
	120		6.6	8.0	9.4	10.7	11.6	12.7	14.3			(15)
Sorghum, kafir	40	6.8	8.5	9.7	11.0	12.3	13.7	15.3	17.3			(17)
	70	6.0	7.7	9.1	11.3	11.5	12.8	14.2	16.0	19.0 ¹		(17)
	90	5.0	7.0	8.4	9.6	10.8	12.0	13.2	14.7	17.0 ¹		(17)
Soybeans	77		5.5	6.5	7.1	8.0	9.3	11.5	14.8	18.8		(18)
	77				7.0	8.0	10.1	12.2	16.0	20.7		(5)
Sugar beet seeds	40			10.0	11.5	12.7	13.9	15.3	17.6	22.6		(19)
	60			9.0	10.0	11.5	12.5	14.1	16.2	19.9		(19)
	80			8.0	9.1	10.4	11.6	12.9	14.7	18.0		(19)
	100			7.0	8.3	9.2	10.4	11.5	13.2	15.8		(19)
Wheat, soft red winter	20				11.0	12.8	14.1	15.3	17.0			(12)
	32				11.0	12.2	13.5	14.7	16.2			(12)
	50				10.2	11.7	13.1	14.4	16.0			(12)
	70				9.7	11.0	12.4	14.0				(12)
	77	4.3	7.2	8.6	9.7	10.9	11.9	13.6	15.7	19.7	25.6	(1)
Wheat, hard red winter	77	4.4	7.2	8.6	9.7	10.9	12.5	13.9	15.8	19.7	25.0	(1)
Wheat, hard red spring	77	4.4	7.2	8.5	9.6	11.1	12.5	13.9	15.9	19.7	25.0	(1)
Wheat, white	77	5.2	7.5	8.6	9.4	10.5	11.8	13.7	16.0	19.7	26.3	(1)
Wheat, durum	77	5.1	7.4	8.5	9.4	10.5	11.5	13.1	15.4	19.3	26.7	(1)
Wheat	30		6.9	9.2	10.4	11.8	13.2	14.5	16.3			(15)
	60		6.1	7.8	9.6	10.7	12.7	13.8	15.3			(15)
	77	5.8	7.6	9.1	10.7	11.6	13.0	14.5	16.8	20.6		(20)
	90		5.3	7.0	8.8	10.3	11.5	12.9	14.3			(15)
	120			6.2	7.4	9.6	10.4	11.9	13.6			(15)
	122	4.0	5.8	6.7	8.1	10.0	10.8	12.6	15.1	19.4		(20)
	32					13.0	14.2	16.0	18.0	21.1		(13)
	68					12.2	13.2	15.1	17.1	20.3		(13)
	104						12.6	14.1	16.3	19.8		(13)
	50		7.9	9.2	10.6	12.7	14.2	15.0	17.3			(21)
	66	5.6	7.1	8.3	9.6	10.9	12.2	13.5	15.0			(22)
	104	4.8	6.2	7.4	8.6	10.0	11.3	12.3	14.2			(22)
	176	2.5	3.7	4.6	5.7	6.7	8.0	9.8	11.5			(22)

¹ Unreliable because of mold growth.

(1) Coleman and Fellows (1955), (2) Karon (1947), (3) Dexter et al. (1955), (4) Weston and Morris (1954), (5) Lammour et al. (1944), (6) Beasley (1962), (7) Houston and Kester (1954), (8) Hogan and Karon (1955), (9) Bukharov (1960), (10) Breeze (1955), (11) Hendemon (1970), (12) Thompson and Shedd (1954), (13) Pinton and Warburton (1971), (14) Gustafson (1972), (15) Harnan (1961), (16) Rodriguez-Arias (1958), (17) Fanton (1941), (18) Remsted and Gaddes (1942), (19) Hall (1966), (20) Becker and Ballant (1966), (21) Young and Nelson (1967), (22) Fichter (1967).

Appendix C

ECONOMIC COMPARISON OF REGENERATED DESICCANT AND CONVENTIONAL CROP DRYING SYSTEMS

In order to estimate the economic characteristics of the regenerated desiccant crop drying concept, a case study has been defined. The case study addresses the installed cost differential between conventional crop drying equipment and regenerated desiccant crop drying equipment required to dry 100 bushels of seed corn per hour from a moisture content of 25 to 15% water by weight.* This represents a nominal moisture removal rate of approximately 600 pounds of water per hour. The influences of escalating fuel costs, depreciation, and days of use per year on payback period are investigated.

DISCUSSION

The case study compares the costs of operation for regenerated desiccant and conventional crop dryers used to dry 100 bu/hr of seed corn on a 24 hr/day basis. Costs for fossil fueled regenerated desiccant and solar regenerated desiccant systems have been estimated based on budgetary estimates of major components obtained from vendors. The payback period for the solar and fossil systems are determined as a function of days of use per year, depreciation, and escalating fuel schedules using economic analyses outlined in Ref. C-1.** The estimated installed costs of conventional fossil fueled regenerated desiccant and solar regenerated desiccant crop dryers are listed in Table C-1. The assumptions used in performing the economic analysis are presented in Table C-2.

* Or 200 bushels/hour from 20 to 15%.

**C-1. Dickinson, W. C., and J. N. Shearer, "Method of Economic Analysis for Comparison of Solar Process Heat Systems," Lawrence Livermore Laboratory, Livermore, Calif., August 1976.

Table C-1

INVESTMENT FOR INSTALLED CROP DRYER RATED AT 100
BU/HR FOR CORN (600 LB/HR WATER REMOVAL RATE)

	Capital Investment
Conventional System	\$ 10,000 – \$20,000
Fossil Fuel Regenerated Desiccant	\$ 42,400.00*

* Represents the increase in installed cost for desiccant system over conventional system.

Table C-2

ASSUMPTIONS FOR ECONOMIC MODEL

20-Year Lifetime

50% Tax Rate

Debt Financing at 8% Interest

Zero Inflation Rate (This assumption is made in order to more easily delineate the influences of escalating fuel costs.)

Various Fuel Price Escalation Schedules (These schedules in effect represent increase in the cost of fuel above the inflation rate for the whole economy.)

Depreciation Schedules

a. Straight Line over 20 Years

b. Accelerated Depreciation (10 Years)

10% Tax Credit on Capital Investment

No Credit for Additional Use of Solar Heat Other Than for Crop Drying (Solar heat used only for desiccant regeneration)

The capital investment for the conventional crop dryer is representative of a fixed site, column-type of dryer rated at 100-200 bushels of corn per hour wherein the drying efficiency is 2200 to 2500 Btu for each pound of water removed from the crop (Btu/lb H₂O). Operational costs for the regenerated desiccant concepts are for fixed site units with drying efficiency of 1000 to 1100 Btu/lb of water removed (Ref. 2^{*}). For operation with solar energy as a primary input, approximately 8000 ft² of concentrating collectors are required to supply approximately 75% of the process energy for desiccant regeneration, and the estimated minimum investment in the solar collecting and storage system is approximately \$150,000.

A useful parameter used to assess the economic merit of capital investment in new equipment is the payback period. Payback period is generally defined as the net initial investment after tax credit divided by net annual cash flow reduction after taxes but before depreciation:

$$\text{Payback Period} = \frac{\text{Net Initial Investment}}{\text{Net Annual Cash Flow}}$$

The payback period for the capital investment difference between regenerated desiccant and conventional crop drying equipment is shown in Fig. C-1 for straight line depreciation over the 20-year lifetime. Payback period is shown for fossil and solar regeneration as a function of days of use per year; the system is assumed to operate 24 hours a day. The influence of fuel cost escalation schedules of 0, 5 and 10% per year are shown parameterically.

Figure C-2 shows the effects of accelerated depreciation on payback period. The solar regenerated system with its higher installed costs is more significantly influenced by accelerated depreciation.

* 2. Ko, S.M., and G.H. Watson, "Desiccant as Drying Agent/Heat Storage Media for Crop Drying by Solar Energy," Lockheed Missiles & Space Company, Huntsville, Ala., LMSC-HREC PR D496963, August 1976.

Fig. C-1 - Payback Period for Desiccant Crop Drying System
(Straight Line Depreciation)

Fig. C-2 - Payback Period for Desiccant Crop Drying System
(Accelerated Depreciation)

For a solar powered system, where the collectors are also used for other purposes, such as for building heating and cooling, the payback period can be significantly shortened. For example, the payback period for 80 days per year of drying (15 years) can be reduced to as low as 7 years depending upon the share of the collector usage for the drying.

Table C-3 is a summary of a cost/benefit analysis example for fossil fueled and solar desiccant crop drying system over conventional open cycle crop drying systems for 100 days per year operation and 10% fuel escalation rate. Net annual savings over conventional systems is \$13,954 for the fossil fueled system and \$8,136 for the solar system, which is equivalent to 5.7 and 3.4 cents per bushel savings in unit drying cost, respectively.

Figure C-3 presents unit drying cost savings per bushel over conventional system costs, in parametric form. It should be noted that the solar system becomes more profitable than the fossil fueled system at a higher number of days per year operation as well as for higher fuel escalation rates. For example, for over 160 days per year operation at 10% fuel escalation, the solar system saves more than the fossil fueled system.

SUMMARY

The regenerated desiccant crop drying system using solar or fossil fueled desiccant regeneration has been compared on an economic basis with conventional crop drying systems. The payback period required to recoup the increase in capital investment of a regenerated desiccant system over that of a conventional system has been quantified and operational costs are compared. Fossil fueled regeneration crop drying systems have a payback period of less than 10 years for typical fuel cost escalation of 5% per year and system use exceeding about 50 days a year. Solar regeneration requires a larger capital investment with correspondingly longer payback periods, but requires significantly less fossil fuel consumption.

Table C-3
COST/BENEFIT ANALYSIS EXAMPLE FOR 100 DAYS/YEAR OPERATION
AND 10% FUEL ESCALATION

Fossil Fueled

Initial Investment over Conventional System: \$42,400

Total Life Cycle Capital Cost over Conventional: \$86,360

Annual Cost over Conventional		Annual Benefit over Conventional	
Debt Retirement (P&I)	\$ 4,318	Fuel Savings	\$18,484
O&M	636	Tax Credit	212
Tax*	6,765		
Total	\$11,719		\$18,696
Net Annual Benefit over Conventional System after Tax			6,977
Net Annual Benefit over Conventional System before Tax			<u>13,954</u>
Unit Cost Savings over Conventional System			5.7 cents/bushel

* Calculated from

$$\text{Tax} = 0.5 (\text{Fuel Savings} - \text{O\&M} - \text{Interest} - \text{Depreciation})$$

Solar

Initial Investment over Conventional System: \$192,400

Total Life Cycle Capital Cost over Conventional: 391,920

Annual Cost over Conventional		Annual Benefit over Conventional	
Debt Retirement (P&I)	\$19,596	Fuel Savings	\$28,694
O&M	2,886	Tax Credit	962
Tax*	3,106		
Total	\$25,588		\$29,656
Net Annual Benefit over Conventional System after Tax			4,068
Net Annual Benefit over Conventional System before Tax			<u>8,136</u>
Unit Cost Savings over Conventional System			3.4 cents/bushel

* Calculated from

$$\text{Tax} = 0.5 (\text{Fuel Savings} - \text{O\&M} - \text{Interest} - \text{Depreciation})$$

Fig. C-3 - Unit Cost Savings from Regenerated Desiccant Systems Over Conventional Drying Systems on a per Bushel Basis

It can be concluded from this case study is that regenerated desiccant crop drying systems, both solar and fossil fueled, have the potential for being cost-competitive with conventional systems while providing 50 to 80% savings in fossil fuel consumption. A major factor, however, is the utilization factor, e.g., days per year of use, indicating that centralized processing is a desirable application. Also for the solar operated system, additional use of the solar collectors during non-drying periods will reduce the effective pay-back time.