THE EFFECTS OF DUST CONTAMINATION

ON THE SORPTION CHARACTERISTICS

OF SILICA GEL

By

SHAH MUHAMMAD FAROUK

Bachelor of Science in Mechanical Engineering
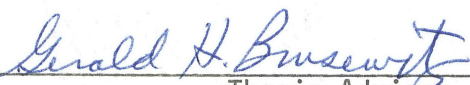Bangladesh University of Engineering and Technology
Dacca, Bangladesh
1963

Master of Science
Texas A & M University
College Station, Texas
1967

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in Partial Fulfillment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY
May, 1979

THE EFFECTS OF DUST CONTAMINATION
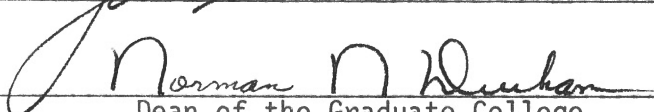
ON THE SORPTION CHARACTERISTICS

OF SILICA GEL

Thesis Approved:

Gerald H. Brusewitz
Thesis Adviser

Myron D. Paine

Earl J. Ferguson

J. W. Weber

Norman N. Durham
Dean of the Graduate College

PREFACE

This study was concerned with the effect of airborne dust particles on the sorption properties of silica gel which has been indicated by earlier researchers to be useful for drying air with the application of solar energy for the agricultural applications of product drying and space dehumidification. The major objectives were to find the effect of fine dust particles on the equilibrium moisture content and on the dynamic sorption rates of silica gel.

The author wishes to express his thanks and deep appreciation to his major adviser, Dr. Gerald H. Brusewitz for his constant guidance and encouragement throughout the course of this study. Appreciation is extended to Dr. Dennis K. McLaughlin of the M.A.E. Department for his encouragement and advices as a member of the advisory committee until he left the OSU campus on a sabbatical appointment. Sincere thanks and appreciation are extended to Dr. Myron D. Paine of the Agricultural Engineering Department, Dr. Earl J. Ferguson of the Industrial Engineering and Management Department, and Dr. John A. Wiebelt of the Mechanical and Aerospace Engineering Department for the encouragement and guidance they provided as the members of the author's advisory committee.

Appreciation is extended to Professor Jay G. Porterfield, former Head of the Agricultural Engineering Department, and to Professor C. T. Haan, Head of the Agricultural Engineering Department, for providing the facilities and financial support which enabled the completion of

iii

this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	=	Correction factor defined in equation 4
Ar	=	Archimedes number
C	=	Capacitance in electrical circuits, farad
Co, C_1, etc.	=	Constants
D	=	Diffusion coefficient for water vapor, m^2/sec
db	=	Dry basis of moisture determination
d_p	=	Diameter of silica gel particles, millimeter
exp	=	Exponent to the base of natural logarithm
f_d	=	Dust contamination factor, fraction
G	=	Superficial mass velocity of air, lb/ft^2 min
H	=	Humidity of air, lb of moisture/lb of air
h_m	=	Mass transfer coefficient for dust free sorbent surface, mass/time
h_{md}	=	Mass transfer coefficient for dust contaminated sorbent surface, mass/time
Ho	=	Depth of desiccant bed, centimeter
Hr, hr	=	Hour
K	=	Mass transfer coefficient, lb/min
k	=	Dynamic sorption constant, Hr^{-1}
K_{cs}	=	Average moisture movement rate, m/sec
M	=	Instantaneous moisture content, % dry basis
Me	=	Equilibrium moisture content, % dry basis
Mo	=	Initial moisture content, % dry basis

MR	=	Moisture ratio, defined with equation 3
P	=	Density of dry silica gel, lb/ft^3
Pa	=	Vapor pressure in air, atmosphere
Pgel	=	Vapor pressure in silica gel, atmosphere
Ps	=	Saturated vapor pressure, atmosphere
R	=	Electrical resistance, ohm
r	=	Radius of an idealized spherical body
Re	=	Reynolds number
RH	=	Relative humidity, percent
Sc	=	Schmidt number
SCFH	=	Flow rate, ft^3/hr at standard condition
Sh	=	Sherwood number
U	=	Superficial air velocity, m/sec
V	=	Electrical potential difference, volt
W	=	Moisture content, dry basis, fraction
X	=	Height of silica gel bed, ft
α	=	A constant depending on particle size
$(\alpha=x)$	=	Statistical significance level, x=probability of Type I error
β	=	Angle of spouting of updraft air
θ	=	Elapsed time, hour

CHAPTER I

INTRODUCTION

The Problem

The drying of agricultural products is a necessity for storage,
handling and processing. Common practices of drying grains involve
passing heated air through grain columns until the moisture content of
grains is reduced to a desired level. Since grains, like all other
hygroscopic materials, tend to reach a hygroscopic equilibrium with its
surrounding, the humidity of the drying air is required to be suffi-
ciently low for drying operations. Heating the air usually serves the
purpose of increasing its moisture removing capacity by lowering the
relative humidity without altering the absolute humidity. An alternate
method of reducing both the absolute and relative humidity of air is by
the use of desiccants. Desiccant dried air makes drying of agricultural
products at near ambient temperature possible without using the costly
vacuum drying method. Low temperature drying is often desirable for
maintaining the quality of dried products and for preserving the
viability of grain seeds (Brooker et al., 1974).

The energy supply needed for conventional drying methods, heated
air drying and refrigeration drying, is immediate during the drying
operation; but supply of external energy for regeneration of desiccants
may be made at convenient times after the use of desiccants in drying
some product. External energy supply for drying may be better managed

1

in desiccant drying by avoiding peak load periods, and the intermittent sources of energy, like the sun and the wind, may also be utilized. Since regenerated desiccants act as sources of stored potential for removing moisture, desiccants may be looked upon as indirect energy storage media.

The problem of energy supply for drying farm products is acute in the developing nations. A workshop on appropriate agricultural technology held in Bangladesh (1975) strongly recommended development of a small scale on-farm grain drying system using available energy sources for preventing loss of stored grains during the highly humid monsoon season. Works of Odigboh (1976) and Koh (1977) indicate successful use of desiccants for grain drying, and the utilization of solar energy for desiccant regeneration.

Commercially available desiccants fall into two broad classes according to their physical properties. Liquid and liquescent desiccants retain their liquidity over a broad range of temperature and moisture content, though some liquescent desiccants become solid at low moisture content. The solid desiccants remain in solid state for all moisture level contents ranging from bone dry to saturation condition over a wide range of temperature. Liquid desiccants usually have high moisture sorption capacity, but most of the liquid desiccants show some corrosiveness (Hougen and Dodge, 1947), and the heat and mass transfer between a liquid desiccant and air requires elaborate systems of pumps, tubing, spray chambers, etc. Lithium chloride is probably the most favored liquid desiccant and it is used in some large process industries due to its high moisture holding capacity (more than 100% by weight, dry basis, at temperatures below 50° C) in spite of the relatively higher

cost and operational complexities of such a system. For small and medium scale grain drying operations where drying equipment is likely to be used intermittently, the costly and complex liquid desiccant systems may not be suitable. Solid desiccants like silica gel, activated alumina, and activated carbon, may be used and regenerated simply by blowing air through a bed or column containing the granulated desiccant. Convenience of use, handling, storage, and the simplicity of the conceivable drying equipment are attractive points in favor of solid granular desiccants for farm use. Among the commercially available solid desiccants, silica gel shows higher equilibrium moisture content than others, including both activated alumina and activated carbon; and according to Hougen and Dodge (1947), it is considered to be one of the most efficient desiccants available. Silica gel is non-toxic and non-liquescent; and it has high moisture adsorption capacity (about 40% of its own dry weight at 90% relative humidity). Silica gel is also known to have selective adsorptivity for various hydrocarbon and aromatic compounds. The potentials of silica gel for drying grains, and air for dehumidification of animal housing, and its regeneration by utilizing solar energy are promising.

One problem which may affect the sorptive qualities of silica gel in agricultural use is the presence of fine dust particles in grain processing areas, and in animal housing. Bundy (1974) studies dust in animal housing; First et al. (1974), reported about discharge of dust particles from grain drying equipment; Avant (1976) found dust particles in grain sorghum storage with mass median diameter of 12 micrometers, and Matlock (1976) found dust particles of similar size in cotton-seed mill areas. Abundance of small dust particles may, therefore, be taken

as an established fact for agricultural environment. Dust particles
can conceivably reduce the available external surface area of silica
gel granules and effect the mass transfer rate. Information on the
effect of dust contamination on the sorptive characteristics of silica
gel is needed for designing systems for drying farm products with
silica gel and for regeneration of the gel. Specific information on
this topic is not available. The present study was undertaken to
obtain quantitative and qualitative information on the effect of dust
contamination on the moisture sorption properties of silica gel.

Objectives

The objectives of this study were to find the effect of fine dust
particles on the equilibrium moisture content, and on the dynamic mois-
ture adsorption and desorption rates of silica gel at different dust
contamination levels (including dust free control), at the relative
humidities and silica gel particle size ranges which are likely to be
encountered in grain drying operations and in solar regeneration of
silica gel. The specific objectives were as follows:

1. To find the equilibrium moisture content of silica gel in
   three particle size ranges at three levels of relative humidity
   as affected by fine dust contamination.

2. To find the dynamic rate of moisture adsorption by silica gel
   as affected by fine dust contamination, gel particle sizes, and
   relative humidity of air at a constant rate of aeration and at
   a fixed dry bulb temperature.

3. To find the dynamic rate of moisture desorption by silica gel
   as affected by fine dust contamination and gel particle sizes

while subjected to a constant rate of aeration at a fixed air temperature and humidity simulating output from solar air heaters.

CHAPTER II

LITERATURE REVIEW

Silica gel has been described by Hougen and Dodge (1947) as a
highly efficient and widely used solid desiccant. It is produced under
controlled conditions from the reaction of a soluble silicate, such as
sodium silicate, and an acid. The product of this reaction sets to a
jelly-like consistency, and is washed free of all acids and undesirable
salts before drying and crushing to desired sizes of particles. Fi-
nally, the grains are heat treated. The controlled drying and heat
treating processes produce networks of fine capillary pores having
average diameter of approximately 2 to 4 nanometers within the gel
particles. These sub-microscopic capillaries are believed to induce
necessary attractive forces for adsorption of various gases and vapors
among which the water vapor is most readily adsorbed (Hougen and Dodge,
1947). Moisture adsorption in silica gel is exothermal as the latent
heat of moisture condensation and an additional amount, "heat of
wetting", is released.

Hygroscopic Equilibrium

The hygroscopic equilibrium of activated silica gel has been
studied by many researchers, and consolidated empirical data in the
forms of vapor pressure isopiestic, moisture isothermal, and similar
graphical forms were published by Hougen and Dodge (1947). Graphical

6

information indicated that the equilibrium moisture content of silica gel increased approximately linearly with the relative humidity of its environment up to 90% relative humidity at temperatures not exceeding 35° C. Equilibrium moisture content decreased with the increase of gel temperature. Jury and Edwards (1971) fitted silica gel equilibrium moisture data into a single Langmuir type equation for a wide range of temperature and humidity, and they also found that the equilibrium moisture content of silica gel shows negligible hysteresis.

Dynamic Sorption Characteristics

Studies on the dynamic sorption rates for granular solids, including silica gel, may be grouped into two categories: a) analysis and experimentation on sorption by hygroscopic particles separately or in thin layer and b) analysis and experimentation on the movement of temperature and moisture front in a thick bed or tall column of granular particles when subjected to a step change in the moisture and temperature of air blown through the bed or column.

The mechanism of sorption by a single grain, or a particle of porous hygroscopic solid material, according to Brooker et al. (1974), may comprise a combination of: a) liquid movement in the capillaries due to surface forces; b) liquid diffusion due to moisture concentration differences; c) surface diffusion of moisture on the pore surfaces; d) vapor diffusion due to moisture concentration difference; e) vapor movement associated with temperature difference and thermal diffusion; and f) water and vapor movement or hydrodynamic flow due to total pressure difference. The vapor diffusion mechanism was emphasized by early researchers, and the analyses of sorption process presented by Newman

(1931), Van Arsdel (1947), and Pearse et al. (1949), were based mainly on the theory of diffusion. Hougen et al. (1940), however, pointed out that while the diffusion process is thought to govern the transfer of moisture from a drying solid material, the capillary attraction in the porous solid must also be taken into consideration. A mathematical solution for the rate of moisture sorption in a spherical body, based on the diffusion theory, was found to be:

$$\frac{M-Me}{Mo-Me} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(\frac{-D\pi^2\theta}{r^2}(2n-1)^2\right) \tag{1}$$

where:

M = Moisture content at an instant.

Mo = Initial moisture content.

Me = Equilibrium moisture content.

D = Diffusion constant for water vapor.

r = Radius of the idealized spherical body.

θ = Elapsed time.

The above equation often failed to predict the rate of drying of real materials. Luikov (1966) developed a mathematical model for the drying of capillary porous products based on the combination of all conceivable mechanisms involved. This model involved a series of second order partial differential equations, and it was often difficult to solve this series of equations due to non-linearity of some parameters and due to imprecise informations on some of the coefficients and constants related to material properties. The Luikov model is, however, considered to be one of the most elaborate ones.

A simple and effective mathematical model, analogous to Newton's cooling equation, is often used in drying of porous solid materials.

It is based on the empirical observation that the moisture content of a hygroscopic material asymptotically approaches its equilibrium with a given environment, and on the assumption that the rate of moisture transfer is directly proportional to the difference between the final equilibrium moisture content and the instantaneous moisture content. Mathematically, this model is:

$$\frac{dM}{d\theta} = k \ (M-Me) \qquad (2)$$

After separating variables and intergrating within proper limits, the solution is obtained as:

$$MR \ (Moisture \ Ratio) = exp \ (-k\theta) \qquad (3)$$

$$and \ MR = (M-Me)/ \ (Mo-Me) \qquad (3a)$$

where:

M = Instantaneous moisture content.

Mo = Initial moisture content.

Me = Equilibrium moisture content.

k = Constant.

θ = Elapsed time.

The constant k is often termed drying constant, drying index, or sorption constant. A correction factor "A" is usually incorporated to this equation for better agreement with grain drying data, and the equation of this simple model, as mentioned by Henderson and Perry (1966), becomes:

$$MR = A \ exp \ (-k\theta) \qquad (4)$$

where A and k are experimentally determined for particular applications.

Analysis of moisture transfer in a deep bed or tall column of hygroscopic material is more complex because a thick bed may be

visualized as a composite body comprising an infinite number of thin layers. The rate of moisture transfer at any given instant is not uniform at all depths of a deep bed, as the entering air reaches equilibrium earlier with the layers near the air inlet. The rate of drying or wetting of the whole mass is primarily controlled by the bed configuration.

Hougen and Marshall (1947), and Hougen and Dodge (1947) reported a method of graphical solution for the problem of drying air in solid desiccant beds. Energy balance consideration and empirical correlation of moisture transfer were used to develop the method. The basic correlations used were:

$$\frac{\partial W}{\partial \theta} = \alpha \ G^{.84} \ (Pa - Pgel) \tag{5}$$

$$W = .55 \ (\frac{Pgel}{Ps}), \ Pgel = 1.82 \ PsW \tag{6}$$

$$Pa = 1.62 \ H \tag{7}$$

$$\text{If } K = 1.62 \ \alpha \ G^{.84} \tag{8}$$

$$\text{and } C_o = \frac{1.82}{1.62} \ Ps \tag{9}$$

$$\text{then } \frac{\partial W}{\partial \theta} = K \ (H - C_o W) \tag{10}$$

and from mass balance

$$G \ \frac{\partial H}{\partial X} = - \ P \ \frac{\partial W}{\partial \theta} \tag{11}$$

Here:

H = Humidity of air.

G = Mass velocity of air based on superficial area.

P = Density of dry silica gel.

α = Constant, depending on grain size.

W = Moisture content of gel, dry basis, fraction.

θ = Time in minutes.

Pa = Vapor pressure in air.

Pgel = Vapor pressure in gel.

Ps = Saturation vapor pressure.

X = Height of silica gel bed.

The solution to the above set of equations involves use of Bessel's functions. Hougen and Dodge (1947) reported a set of graphical solutions based on earlier works on analogous cases of heat transfer. These graphical solutions were effective for isothermal sorption process only. Deep bed drying of agricultural material was analyzed by Hukill (1947), and Bakker Arkema et al. (1967). Computer simulation of deep bed drying, utilizing numerical integration technique was applied by Hamdy and Barre (1970) to most hygroscopic materials. A purely empirical approach for determining the dynamic adsorption rate of a silica gel column when moist air is spouted through it was reported by Kmiec (1975). The coefficients of both mass and heat transfer for an adiabatic process was found to be highly affected by the velocity of air flow. The actual correlation reported by Kmiec (1975) was:

$$K_{cs} = C_1 \ U^{.687} \ d_p^{1.007} \ Ho^{-1.227} \ (\tan \beta/2)^{.915} \tag{12}$$

$$\text{and } Sh = C_2 \ Re^{.414} \ Sc^{.333} \ Ar^{.031} \tag{13}$$

where,

K_{cs} = Average moisture movement rate.

U = Superficial air velocity.

d_p = Average diameter of silica gel particles.

Ho = Bed depth.

β = Angle of spouting for updraft air flow.

Sh = Sherwood number.

Re = Reynold's number.

Sc = Schmidt number.

Ar = Archimedes number.

C_1 & C_2 = Constants.

This correlation was reported to agree with experimental data quite well. The effect of the particle size of silica gel on the rate of moisture transfer is indicated well in the above correlation. The ranges of variables used in the above experiment were not very wide. An earlier work on the adiabatic sorption of moisture in a fixed bed of silica gel was reported by Bullock and Threlkeld (1966) who used numerical method of solving a system of differential equation using a high speed digital computer. The computer solutions predicted the moisture content and temperature of air after passing through a bed of silica gel when the properties of air at the inlet and the condition of the silica gel bed at the beginning of operation were known. The experimental data reportedly agreed well with the simulation and the slight disagreement was thought to be due to imprecise information on the vapor pressure values used in calculation.

Energy Management Considerations

Silica gel and similar other desiccants which can be regenerated for repeated use may be considered as media for indirectly storing energy. Instead of applying energy from an available source directly to a product for its drying, the energy may be used to regenerate a mass of moist desiccant which may be used subsequently for the product drying. Thus, energy from some convenient, cheap, or intermittent source may be utilized to create moisture removing capacity in silica

gel for product drying purposes. The total energy content of silica gel at different temperatures and moisture levels in equilibrium with air of known temperature and humidity was calculated and plotted on a modified psychrometric chart by Close and Banks (1972). This chart, called "Silica Gel Characteristic Chart" made the visualization of silica gel sorption operations and calculation of energy use much more convenient.

The capacity of hygroscopic materials, like silica gel, for storing energy has been reported by Close and Dunkle (1977) to be much higher than the capacities of non-hygroscopic materials of similar mass and specific heat when used to store energy for drying operations. For example, if ambient air temperature is 29.7° C, absolute humidity is .018 kg/kg of dry air, and this air is heated to 56° C, the amount of total recoverable energy that can be stored in the gel for subsequent drying use is approximately 13.5 times the amount of recoverable sensible energy that could be stored in a non-hygroscopic medium of similar mass and specific heat as the gel. The relative advantage of the gel would, however, diminish if higher temperature levels and high specific heat materials are used for storing sensible heat, but when storing solar energy in a low cost medium is considered, the hygroscopic materials obviously show relative advantage over the non-hygroscopic ones. Moreover, Close and Dunkle (1977) pointed out, the sensible heat loss from a hygroscopic mass does not reduce its drying capacity. Hence, thermal insulation is not needed for storing drying energy in a desiccant as long as it can be kept sealed from moisture, whereas non-hygroscopic materials must be kept insulated from its surrounding to prevent energy loss. A study on optimizing the total cost

of timber drying reported by Duffie and Close (1978) shows that an adsorbent heat storage system had less overall annual cost than a non-adsorbent heat storage when solar collectors were utilized.

Analysis of deep bed drying of moist silica gel with solar energy with intended use for farm crop drying has been reported by Koh (1977). Computer simulation of adiabatic drying processes, when the temperature and humidity of air supplied from a solar collector to the drying bed is known, has been verified through actual experiments. Azer et al. (1979), reported similar results in which the numerical solution of heat and mass transfer equations applied to silica gel regeneration agreed with experimental results in general, though the experimental values of the moisture content of the gel were consistently slightly (approximately 5% moisture on the average) higher. Temperature range of the drying air used in this work was 50 to 80° C.

Limitations of Operating Conditions

Silica gel can be used over a wide range of temperature, humidity, and spouting air velocity, but there are some practical limitations. Ledoux (1948) reported that at higher velocities fluidization occurs in silica gel beds and it tends to pulverize the gel grains. The air velocity at which fluidization occurs depends on the gel grain size and bed geometry; finer grain sizes fluidize at much lower velocities than the coarser sizes. The superficial air velocity used by most researchers working with silica gel, as reported above, seemed to be in the range of 15 to 30 meters per minute for coarse (3 to 16 mesh per inch) gel grains. Silica gel regeneration time decreases with increase of temperature, but Kotb (1968) cautioned that at temperatures exceeding

300° C the internal structure of the capillaries in silica gel may be affected so that the moisture adsorbing capacity is lowered. Practical temperature of regeneration with solar energy, however, is much lower (in the range of 50° C to 80° C) as found by Koh (1977).

Dust Contamination

Prevalence of dust in agricultural industries is a known fact which was not subjected to quantitative analysis until recently. Bundy (1974) analyzed particle size distribution in swine buildings and found that fine dust particles with sizes in the order of 10 micrometers were abundant, with the total particle count of up to 1800 per 0.01 cubic foot of air. These dust particles, Bundy (1974) reported, could be reduced by ionization methods, but could not be totally eliminated. Avant et al. (1976), found that dust particles with mass median diameter of 12 micrometers abound in grain sorghum storage, and particles of small sizes (less than 20 micrometers) were difficult to remove from air. Matlock (1976) found dust particle concentration in cotton seed mills as high as 51.3 mg/m^3 for sizes less than 100 micrometers. First et al. (1974), found that about 99.9% of solid particulates discharged from grain drying equipment were in the size ranges of 10 micrometers or larger; further division of size ranges was not reported. Martin (1977) reported presence of small sized dust (less than 125 micrometer) in corn processing areas. Quantitative information on the dust particles suspended in the air in grain drying rooms and in animal housing is scarce. From common experience, the existence of dust particles in the air of agricultural industries may be taken as an established fact. The smaller dust particles (20 microns and less in

diameter) are of main concern since these cannot be totally removed by ionization (Bundy, 1974) or by filtration at acceptable cost.

Silica gel to be utilized for storing solar energy in the form of drying potential for subsequent use in drying grain or in dehumidifying air is subject to contamination by air borne dust particles. Information on the effect of dust contamination on the sorption properties is important for the design and operation of such a system. Since the gel grains adsorb and desorb moisture through the exposed surface, and since the fine capillaries in the gel are known to play a major role in moisture sorption, dust deposits on the surface of gel particles can possibly interfere with the sorption process. Hubard (1954) mentioned that fine dust particles could adversely affect silica gel's capacity of drying gases to very low dew point conditions. Bullock and Threlkeld (1966) observed some change of gel properties due to accumulation of minute foreign particles within the pores of silica gel, but they did not elaborate on this observation. Quantitative and specific information on the effect of fine dust on the sorption characteristics of silica gel could not be found.

CHAPTER III

MATERIALS, EQUIPMENT, AND METHODS

Silica Gel

Commercially available silica gel in three particle size ranges was used in experiments. The selected size ranges were: 3-8 mesh size (Davison grade 01), 6-16 mesh size (Davison grade 05), and 28-200 mesh (Davison grade 12). Both grade 01 and grade 05 silica gel are widely used in gas drying operations. The grade 12 (28-200 mesh) gel is not commonly used in gas drying, but it was included in the experimental plan in order to obtain information on the effect of dust contamination on the finer grained silica gel as well as on the more commonly used coarser grained gels. Sufficient quantities of silica gel for all the three grades were obtained in 2.2 to 11.3 kilogram sized containers. Required quantities of silica gel for each experiment were collected from the particular gel container. The containers were manually tumbled and randomly shaken to assure uniformity of the particle size distribution from sample to sample. Container lids were promptly replaced after collection of samples to prevent unwanted adsorption of moisture from the atmosphere. Samples were collected in small pre-weighed bottles and the bottle lid was replaced promptly after collection of a sample to keep the sample isolated from the atmosphere.

Some relevant properties of silica gel have been summarized in
Table I. The particle size distribution in the three grades of silica
gel used was also determined experimentally. A set of standard Tyler
sieves and a Ro-Tap shaker were used, and the particle size distribu-
tion was determined by following the standard procedure described by
Henderson and Perry (1966).

<center>Dust Contaminant</center>

Dust particles expected to be encountered in the agricultural
product processing operations, and in animal housing, may vary in
characteristics. The review of literature indicated the predominance
of 10 to 20 micrometer sized dust particles. A standardized dust used
in testing of filters for various scientific and industrial applica-
tions was obtained from a scientific and industrial supply source.
This dust contained about 70% silicon dioxide, and it was chemically
inert for most applications. The chemical composition of this silica
dust was similar to the composition of silica gel, but the dust
particles lacked the microscopic capillary system which gave the acti-
vated gel its tremendous hygroscopic capacity. The dust obtained from
the supplier was in the size range of 10 to 20 micrometers. The actual
particle size distribution in the experimental dust was analyzed at the
Fluid Power Research Center of the Oklahoma State University following
a procedure described by Moore (1979) in compliance with the standards
specified by the International Standard Organization (ISO) in its stan-
dard specification No. ISO 4402-1977(E). The properties of the silica
dust used are shown in Table II, and the particle size distribution of
the dust is shown in Appendix A (Table XVII and Figure 15).

TABLE I

SOME PHYSICAL AND CHEMICAL PROPERTIES
OF SILICA GEL*

Physical Properties:

Bulk Density	624-720 kg/m^3
Particle Density	1200 kg/m^3
Average Surface Area	750-800 m^2/g
Average Pore Volume	430 mm^3/g
Average Pore Diameter	2.2 nm
Specific Heat	0.92 kJ/kg K
Thermal Conductivity (Particles)	0.14 W/m K

Particle Diameter and Surface Area/Volume Ratios -

Tyler Mesh Range	Dia., mm	Area/Vol., m^2/m^3
3-8	3.9	919
6-16	1.9	1,887
28-200	0.25	14,173

Chemical Composition (Dry Basis):

Silica as SiO_2	99.84%
Al_2O_3, TiO_2, and Other Minerals	0.16%

*Information adapted from Grace (1966).

TABLE II

SOME PROPERTIES OF STANDARD SILICA DUST*

Bulk Density	2194 kg/m^3
Chemical Composition:	
Silica as SiO_2	68.5%
AL_2O_3	16.0%
Fe_2O_3	4.6%
Na_2O	4.6%
CaO	3.0%
Others	3.3%

*Information obtained from the Fluid Power Research Center of the Oklahoma State University, Stillwater, Oklahoma.

Equipment and Facilities

Controlled Environment

Two controlled environment chambers were available at the Agricultural Engineering Laboratories of Oklahoma State University for the present research work. A Hotpack Unit, self contained with shelved space and temperature and humidity control, was available for conducting the moisture sorption tests. An AMINCO-Aire unit for supplying air at controlled temperature and humidity levels was also available, and it was connected with an insulated environment chamber for conducting controlled environment experiments on the sorption properties. The Hotpack Unit was used for all adsorption tests at 25° C, and the AMINCO unit was utilized for the desorption tests at 50° C in order to take the advantage of the operating characteristics of those machines during the period while the present experimental works were conducted.

The temperature and relative humidity levels inside each controlled environment chamber were continuously monitored with a pre-calibrated hygro-thermograph in addition to indicative thermometers and hygrometers installed in those chambers. The controlling mechanisms in the two units described above could normally maintain temperature level within $\pm$ 1° C of the set point, and the relative humidity within $\pm$ 2.5% RH of the desired level. Any deviation from these limits of temperature and humidity variation was recorded on the hygrothermograph, and appropriate measures, including aborting an experiment if variations could not be promptly removed, were taken to avoid experimental errors.

Aeration and Airflow Measurement

Gel sample containers in the form of miniature aeration bins were made of plexiglass tube and 90 mesh (per inch) wire screen. These miniature bins or sample containers were approximately 110 mm tall with an internal diameter of 90 mm and an external diameter of approximately 102 mm. The wire mesh screen was fitted approximately 25 mm above the bottom edge of the container.

Plenum chambers, sized approximately 150 mm x 150 mm x 180 mm high, were made of sheet metal. The top of each plenum chambers had an opening of approximately 85 mm diameter with sponge-rubber cushion for installing the miniature bin. The plenum chambers were individually supplied with air from 1/125 H.P. motor-blowers with rated capacity of blowing 1.7 m^3/min of free air or 0.65 m^3/min at 12.5 mm of water pressure. The blower inlets had movable cover plates for controlling the discharge rate, and the blowers were connected with their respective plenum chambers with short pieces of flexible hose pipe. The plenum chambers had nipples for connecting pressure gages.

A rotameter type airflow measuring instrument, Dwyer Rate Master Flow Meter, in the calibrated range of 50 to 400 SCFH (1.41 to 11.3 standard m^3/hr) of air was used along with a Dwyer Micromanometer for measuring pressure drop across the experimental samples of silica gel in the miniature bin for the desired airflow rates. A Magnehelic dial type pressure gage, calibrated against the Dwyer Micromanometer, in zero to two centimeter water pressure range was used for monitoring the plenum chamber static air pressure during aeration of silica gel samples.

Other Equipment and Facilities

Two single pan balances were used for all weight measurements. One of these had a sensitivity of 0.001 gram and it was used for checking sample weights for all moisture content determination tests. The other balance was highly damped and quick acting type, with a sensitivity of 0.01 gram, and it was used for checking change of sample weights at specific time intervals during aeration for the dynamic sorption characteristic tests.

An air oven with heater control for maintaining set temperature was used for determining moisture content of all experimental samples. The control of the oven was set to maintain a temperature of $120 \pm 2°$ C for moisture content determinations.

A set of standard Tyler sieves and a Ro-Tap Shaker was used for analyzing particle size distribution of the three grades of silica gel used in the experiments.

The services of the Fluid Power Research Center of the Oklahoma State University were obtained for analyzing the size distribution of the experimental dust particles, but all other experimental works were conducted at the Agricultural Engineering Laboratory of the Oklahoma State University.

Experimental Plan and Procedures

Plan of Experiments

The experiments were planned in three groups for the three types of silica gel used, since all three types of gel were not available at the beginning of the experimental works. The experiments were conducted

in the following sequences.

1. Sorption tests with 6-16 mesh (grade 05) silica gel.

    a) Determination of equilibrium moisture content of silica gel for three levels of dust contamination (0, 2, and 5% by weight) and three levels of relative humidity (60, 75, and 90% RH). Completely randomized factorial combinations -- three determinations for each combination -- at constant temperature of 25° C.

    b) Determination of equilibrium moisture content of the experimental dust at the above mentioned three levels of relative humidity at 25° C.

    c) Determination of pressure drop -- airflow rate relationship for the gel sample and making choice of a suitable sample size and airflow rate for the experiments.

    d) Determination of the dynamic moisture adsorption characteristic of the gel samples at three levels of dust contamination and three levels of relative humidity, as above, at 25° C and at a constant rate of aeration. Completely randomized factorial combination -- three determinations for each combination.

    e) Determination of the dynamic moisture desorption rate characteristics of the gel samples, at three levels of dust contamination, as above, at a fixed temperature (50° C) and relative humidity (20% RH) for the gel samples initially equilibrated to approximately 36% moisture content (dry basis, useful concentration) -- three determinations for each factor of dust level.

2. Sorption tests with 3-8 mesh (grade 01) silica gel. Identical steps "a", "c", "d", and "e" as above.

3. Sorption tests with 28-200 mesh (grade 12) silica gel. Identical steps "a", "c", "d", and "e" as above.

4. Equilibrium moisture determinations at 50° C and 20% RH.

    a) Equilibrium moisture content of silica gel for three levels of gel type (Grades 01, 05, and 12), and three levels of dust contamination levels (0, 2, and 5% by weight) -- completely randomized factorial combinations -- three simultaneous determinations for each combination.

    b) Equilibrium moisture determination for the dust at 50° C and 20% RH.

5. Supplementary and repetition tests, for the experiments which had to be aborted due to procedural mistakes, equipment malfunctions or for obtaining additional equilibrium moisture content (EMC) data at 50% RH.

Equilibrium Moisture Content of Silica Gel

Standardized procedure for determination of moisture content of silica gel could not be found in published literature. A preference for relatively low (90° to 150° C) temperature levels for drying silica gel in oven have been indicated by some researchers including Hubard (1954) and Koh (1977). Complete removal of water molecules from silica gel particles require a higher temperature level, above 300° C, but such high temperature can reportedly cause reduction of moisture adsorption capacity of silica gel (Hougen and Dodge, 1947). Regeneration or drying temperature is limited to a maximum of 150° C for

practical purposes, and silica gel dried at such temperature levels
(90° to 150° C) are considered to be dry for useful purposes, and the
moisture content based on dry material content estimated from such low
temperature drying is usually presented as dry basis moisture content
(Hougen and Dodge, 1947) even though the "dry material" may actually
contain up to 5% residual moisture by weight.

The practice of including residual moisture in silica gel with
the dry material weight was followed for calculating equilibrium mois-
ture content for the present experiments, and a temperature level of
120° C was chosen as the average of temperature levels used by many
other researchers.

Equilibrium moisture contents (EMC) of all gel samples were deter-
mined by using air-oven method after the gel samples attained equilib-
rium with air at a desired level of temperature and humidity. Three
samples of a type of gel under investigation, having approximately 30
grams of gel in each sample contained in open petri dishes, were exposed
to air inside a controlled environment chamber. Attainment of hygro-
scopic equilibrium with air inside the chamber was indicated when the
gel samples ceased to change mass. A 48 hours exposure was allowed
before recording the final equilibrium weight of the samples. The
samples and their petri-dish containers were then transferred to an air
oven maintained at a temperature level of 120° C. Sample weights were
checked at intervals of 3 to 12 hours. The samples usually reached
minimum weight within a 12 hour period, but 24 hours of oven drying time
was allowed to all samples before recording the dry mass data. The dif-
ference of the equilibrium weight and the dry weight of a gel sample,
expressed as a percentage of the dry weight, gave the equilibrium

moisture content of the gel sample for the relative humidity and tem-
perature at which it was first equilibrated. This equilibrium moisture
content data was actually the useful moisture content (dry basis) of the
gel at equilibrium with a specific environment.

The equilibrium moisture content of dust contaminated gel samples
were found in the above mentioned method after the dust contamination
level was assured by pre-mixing measured quantities of dust and gel, as
described elsewhere.

Equilibrium Moisture Content of the Dust

Equilibrium moisture contents of the experimental dust were deter-
mined in a method similar to the one described before for finding the
equilibrium moisture content of silica gel. Approximately 10 grams of
dust samples, contained in open petri dishes, were allowed to establish
hygroscopic equilibrium with air at desired temperature and humidity
levels inside the controlled environment chambers for a minimum of 72
hours. These samples were then dried in the air-oven, described earlier,
at $120 \pm 2°$ C for a period of 48 hours. Equilibrium moisture content
was calculated from the difference between equilibrium weight and the
dry sample weight, expressed as a percent of the dry sample weight.

Dust Contamination Mixing

Dust contamination of the silica gel was accomplished for the
present experiments by pre-mixing dust and gel particles. Measured
quantities of the dust, as required for a desired level of contamination
(2% or 5% by weight), was mixed with a measured quantity of silica gel
in a small bottle by shaking the bottle manually with random motion for

approximately one minute. There was no quantitative measure of the uniformity of this mixture, but thorough mixing was indicated by a uniform light grey color of the mixture. Uniformity could not be attained for contamination levels higher than 5% of dust in the dust and gel mixtures. Dust contaminated samples are shown in Figure 1.

Airflow and Pressure Drop Measurement

It was observed that approximately 150 grams of the grade 01 (3-8 mesh) and grade 05 (6-16 mesh) gel make a bed thickness of about 25 millimeters in the miniature aeration bins. This thickness was considered to be the maximum for shallow bed drying conditions, since thick or deep bed drying conditions reportedly apply to beds thicker than 25 mm (Hougen and Dodge, 1947). Gel sample size was, therefore, chosen to be 150 grams of gel for the 3-8 mesh and the 6-16 mesh silica gel.

The plenum chamber, along with a miniature bin containing gel samples was connected to the outlet of the Dwyer Flow Master rotameter (described earlier) while the inlet of the rotameter was connected with a compressed air source through a pressure reduction valve. The pressure monitoring nipple was connected to a Dwyer Micromanometer. The arrangement made air to flow in a series through the Flow Master rotameter, the plenum chamber, the silica gel bed in the bin, and discharge to the atmosphere when the inlet to the rotameter was opened. Pressure decreased at the inlet of the rotameter to slightly above atmospheric pressure to make air flow through the system. Avoidance of higher pressure was necessary for obtaining accurate flow measurement data from the rotameter. Airflow through the system was allowed to stabilize at different rates while the rate of flow and the corresponding pressure at

Figure 1.   Dust Free and Dust Mixed Samples of Silica
            Gel in 90 mm Diameter Plexiglass Aeration
            Bins

the plenum chamber were noted. Different flow rates, below the flow rate at which the silica gel particles were fluidized or disturbed, were used to obtain sufficient information.

The depth of gel bed, as selected for the 3 to 8 mesh and 6 to 16 mesh gel had to be changed for the 28-200 mesh gel since these fine grained gel particles offered much higher air resistance and tended to fluidize at much lower flow rates than in cases of the other types of gel. Sample size for the 28-200 mesh (Grade 12) gel was chosen to be 75 grams for the above reasons. Figure 2 shows equipment used for tests.

Aeration for Adsorption and
Desorption of Moisture

A complete set of aeration equipment comprising a motor-blower, plenum chamber, and a miniature bin or sample container, was placed in each of the two controlled environment chambers used for the experiments. The Hotpack Chamber was used for all adsorption tests and the Aminco unit was used for all desorption tests. Figure 3 shows the Hotpack unit in use.

Prior to each adsorption test the Hotpack unit was set to the desired relative humidity level at 25° C temperature as per the experimental plan. Required quantity of a gel samples for aeration, and an additional 30 grams for initial moisture content determination, were drawn from the gel container. The gel was mixed with a measured quantity of dust, if required to do so as per the factorial plan of experiments, and aeration of the experimental sample started as soon as the gel or the gel-dust mixture was evenly spread in the miniature bin and the bin was placed on the plenum chamber. The aeration bin was weighed
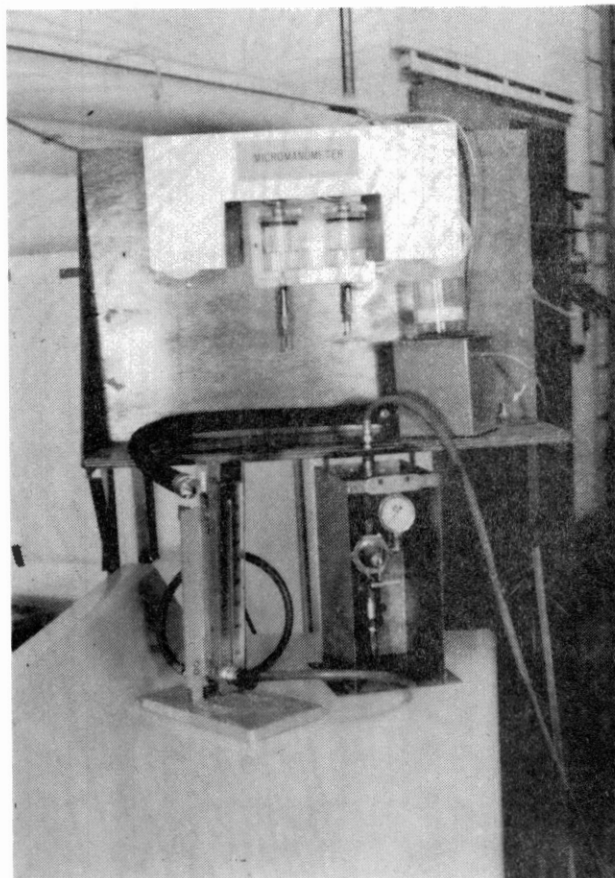
Figure 2. Airflow and Pressure Drop
Measurement Equipment
Showing Pressure Reduc-
tion Valve, Flowmeter,
Plenum Chamber, Miniature
Bin, and Micromanometer
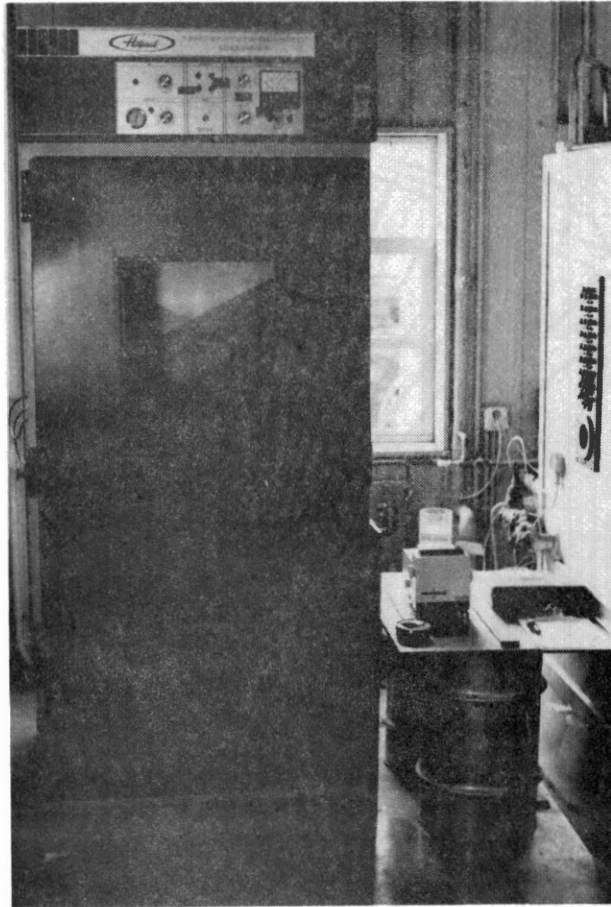
Figure 3. A Controlled Environment
Chamber Containing
Aeration Equipment, and
a Balance for Checking
Sample Weight

on a single pan balance at specific time intervals to obtain the data of moisture adsorption or desorption of the gel sample in the bin as a function of the elapsed time of aeration. The aeration process had to be briefly interrupted for 20 to 30 seconds for each weighing; since the minimum time interval between two consecutive weight checks was 15 minutes, the 20 to 30 second interruption was considered to have negligible effect on the total amount of moisture adsorbed or desorbed by the gel sample. The time interval for weight check was increased after the first hour as the sample gradually neared the hygroscopic equilibrium with the air spouted through it and the rate of moisture sorption decreased.

The temperature and the relative humidity condition of the air inside the chamber which was being spouted through the gel sample bed were monitored during the experiments. The loss of conditioned air each time the environment chamber was opened for checking sample weight was minimized by sealing the whole front side of the chamber with a transparent plastic sheet, leaving only a small opening through which the aeration bin could be taken out and put back.

The rate of airflow was monitored indirectly by checking the plenum chamber pressure during aeration. Plenum chamber pressures maintained for the different grades of silica gel are shown in Table III.

The rate of airflow could be adjusted by adjusting the covering of the motor blower inlet. The required opening of the blower inlet for the desired plenum chamber pressure and airflow rate for any particular gel type was found from trial runs conducted prior to actual experiments. A dial type pressure gage capable of indicating pressure difference down to 0.5 mm water pressure, and calibrated against a micromanometer was

used to monitor the plenum chamber static air pressure during the dynamic sorption experiments. Figure 4 shows the equipment used.

TABLE III

GEL SAMPLE SIZES, AIRFLOW, AND PLENUM
PRESSURES USED IN AERATION

Gel Type	Gel Sample Size	Airflow Rate	Static Air Pressure in Plenum Chamber
3-8 mesh (Grade 01)	150 grams	320 SCFH	5 mm of water
6-16 mesh (Grade 05)	150 grams	320 SCFH	8 mm of water
28-200 mesh (Grade 12)	75 grams	120 SCFH	5 mm of water

Procedure followed during the desorption tests was similar to the one described above for the adsorption tests. The Aminco unit supplied environment chamber, at a temperature of 50° C and a relative humidity of 20%, was used. The gel samples, contained in the miniature bins were first aerated at 25° C and 75% RH in the Hotpack chamber to acquire approximately 36% moisture content before subjection to desorption by spouting the 50° C, 20% RH air in the Aminco supplied chamber. The plenum chamber pressure and the sample size for the desorption experiments were identical to those used for the adsorption tests for each type of gel.
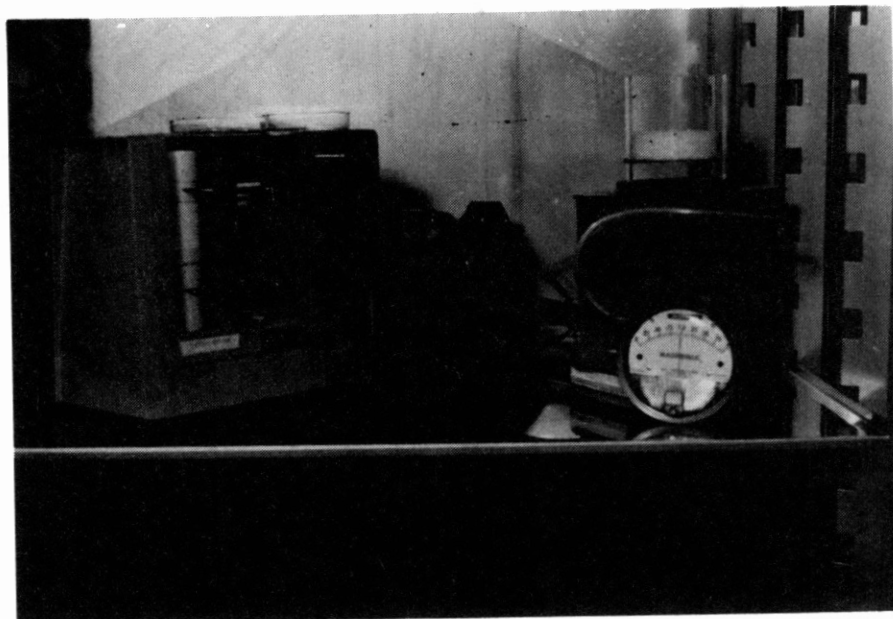
Figure 4.   Aeration Equipment Inside Controlled
            Environemnt Chamber Showing Motor-
            Blower, Plenum Chamber, Aeration Bin
            Containing Silica Gel, Pressure Gage,
            and Hygrothermograph

CHAPTER IV

RESULTS AND DISCUSSION

Equilibrium Moisture Contents

The equilibrium moisture contents of the experimental dust, silica gel, and the dust contaminated silica gel were found according to the experimental plans.

The relative humidity and temperature levels used for finding the equilibrium moisture contents of the experimental silica dust were with those used for other experiments. The results of the test are shown in Table IV. The moisture content of the experimental dust at 50° C temperature and 20% relative humidity was very low, and it was estimated to be less than 0.1% for the present experimental purpose.

TABLE IV

EQUILIBRIUM MOISTURE CONTENTS OF
THE EXPERIMENTAL DUST

Temperature C	RH %	Moisture Contents % d.b.			Average % d.b.
25	50	1.00	0.96	0.96	0.97
	60	1.12	1.05	0.98	1.06
	75	1.42	1.36	1.45	1.41
	90	1.63	1.72	1.75	1.70
50	20	Less than 0.1			<0.1

The moisture content of the dust contaminated gel samples was calculated from the data of the total moisture content of the experimental sample, and the moisture content of dust at the particular temperature and relative humidity level. The recorded moisture content data shows dry basis moisture content determined by using air-oven method as described elsewhere.

The equilibrium moisture contents of silica gel found experimentally are shown in Table V. The data shows consistent results for all the three replications of the experiments. The increase of equilibrium moisture contents at 25° C with the increase of relative humidity is indicated by the data, but the effect of dust content and the particle size ranges of silica gel are not apparent.

Analyses of variance were performed on the equilibrium moisture content data to test the statistical significance of variations due to the different factors involved. Separate analyses were done for the equilibrium moisture data at 25° C and at 50° C. The analyses are shown in Tables VI and VII. The very high significance of relative humidity on the equilibrium moisture content, as shown in Table VI, conformed with the known characteristic of silica gel that the equilibrium moisture content at any particular constant temperature is a function of the relative humidity. The particle size range of silica gel, as indicated by the commercial grade designations of the silica gel used, was not found significant. This was also expected, since the published equilibrium moisture data of silica gel (Hougen and Dodge, 1947; and Hubard, 1954) do not indicate any effect of silica gel particle size on the equilibrium moisture content. The dust contamination level and its interaction with other factors were not found significant

TABLE V

EQUILIBRIUM MOISTURE CONTENTS OF SILICA GEL

Temp. (°C)	RH (%)	Silica Gel Grade	Dust Level (%)	Experimental Values of EMC (% d.b.)			Average EMC (% d.b.)
25	50	05	0	28.52	28.30	28.86	28.56
			5	28.31	28.74	28.72	
25	60	01	0	32.40	31.84	32.05	
			2	31.47	32.21	32.22	
			5	32.24	31.89	31.63	
		05	0	32.00	32.54	31.50	
			2	32.25	30.84	32.41	31.99*
			5	31.40	32.50	32.03	
		12	0	31.27	32.60	32.01	
			2	32.67	31.40	31.93	
			5	32.42	31.76	32.54	
25	75	01	0	36.05	35.39	36.53	
			2	35.82	35.65	36.84	
			5	36.44	36.20	35.76	
		05	0	35.18	35.80	36.91	
			2	35.33	36.83	35.94	36.09*
			5	35.75	36.90	36.14	
		12	0	36.10	35.00	36.92	
			2	35.34	36.74	36.30	
			5	36.22	36.51	35.93	
25	90	01	0	37.46	37.60	38.00	
			2	37.02	37.81	38.63	
			5	37.34	38.44	38.50	
		05	0	38.15	37.60	37.49	
			2	37.82	38.40	38.01	37.90*
			5	38.34	37.74	37.82	
		12	0	37.38	38.34	37.50	
			2	37.50	37.91	38.20	
			5	38.42	38.10	37.70	
50	20	01	0	10.61	9.92	10.40	
			2	11.04	9.91	9.80	
			5	10.40	11.20	9.67	
		05	0	10.00	10.43	9.84	
			2	10.60	9.87	10.10	10.31
			5	9.84	10.66	10.31	
		12	0	9.91	11.41	10.43	
			2	11.50	9.88	10.00	
			5	10.02	10.90	9.85	

*LSD of Mean EMC Values at 60%, 75%, and 90% RH = 0.357, at $\alpha=0.01$.

TABLE VI

ANALYSIS OF VARIANCE OF THE EQUILIBRIUM MOISTURE
CONTENT DATA - FOR 25° C TEMPERATURE AND 60%,
75%, AND 90% RELATIVE HUMIDITY LEVELS

Source	Degrees of Freedom	Sum of Squares	F Ratio	Significance Level*
Corrected Total	80	513.2637		
Gel Grade	2	0.0408	0.06	0.94
RH	2	494.2536	749.67	0.0001
Dust	2	0.4429	0.67	0.52
RH x Gel Grade	4	0.0843	0.06	0.99
Gel Grade x Dust	4	0.0687	0.05	0.99
RH x Dust	4	0.2910	0.22	0.92
RH x Gel Grade Dust	8	0.2815	0.11	0.99
Error	54	17.8009		

*Probability of error in rejecting a null hypothesis or no
significance of the source of variation.

TABLE VII

ANALYSIS OF VARIANCE OF THE EQUILIBRIUM MOISTURE
CONTENT DATA - FOR 50° C TEMPERATURE AND
20% RELATIVE HUMIDITY

Source	Degrees of Freedom	Sum of Squares	F Ratio	Significance Level*
Corrected Total	26	7.1343		
Gel Grade	2	0.2835	0.39	.68
Dust	2	0.0035	0.00	.99
Dust x Gel Grade	4	0.2551	0.17	.95
Error	18	6.5922		

*Probability of error in rejecting a null hypothesis of no
significance of the source of variation.

for the equilibrium moisture content. The moisture contained within silica gel particles at equilibrium with the surrounding air was not effectively altered by the presence of up to 5% dust particles. Identical results were found from the analysis of equilibrium moisture data taken at 20% relative humidity and 50° C; dust level, particle size ranges, and their interactions were not found significant. The total moisture holding capacity of silica gel was not affected by the presence of dust in the inter-particle space of silica gel.

Finding that the equilibrium moisture of silica gel was affected only by the relative humidity level, justified computation of average moisture content values at each relative humidity and temperature combination taking data from all levels of dust contamination. The least significant difference (LSD) of the average equilibrium moisture contents was computed at 99% confidence level (i.e. α=0.01) and the differences among the average values of moisture content at the different relative humidity levels were again found significant. The average values of moisture content at equilibrium condition are shown in Table V and a graphical representation of the equilibrium moisture contents' dependence on relative humidity level is shown in Figure 5.

The average values of equilibrium moisture contents found experimentally here are close to the published data (Hougen and Marshall, 1947; Hubard, 1954; and Grace, 1966). The differences between the published data and the experimentally found values of silica gel's equilibrium moisture content at the selected relative humidity and temperature levels were not over one percent moisture content. Such small differences can be accounted for from the difference in silica gel characteristics among batches of manufacture, as reported by Hubard (1954).
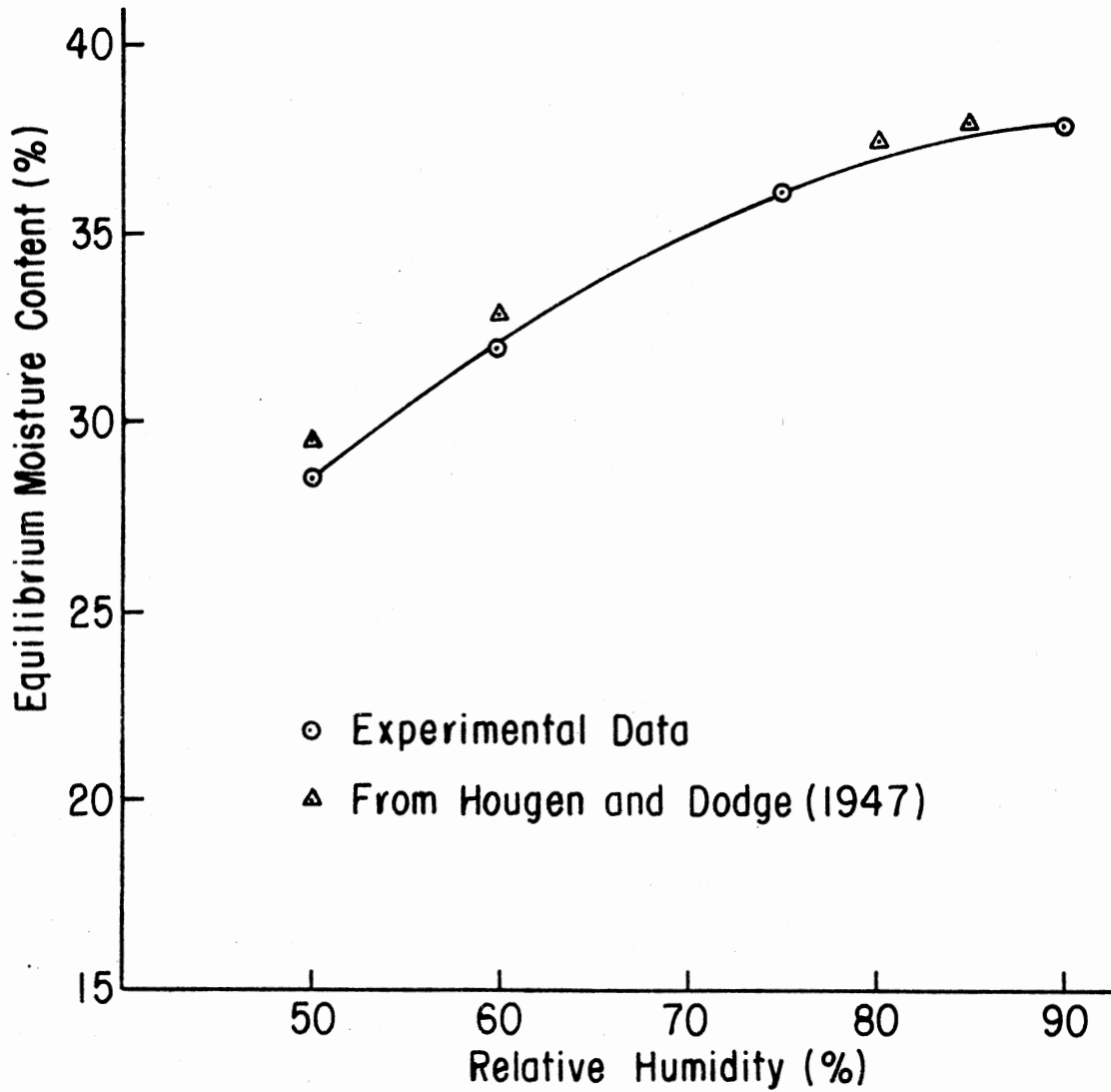
Figure 5.   Equilibrium Moisture Content of Silica Gel at
            25° C, Averaged Over All Dust Levels and Gel
            Particle Sizes

The concept of equilibrium moisture content of a hygroscopic material does not take the time factor or the rate of moisture transfer into consideration. With this concept in effect, the ways in which contaminating materials could alter the moisture holding capacity of silica gel may be categorized in the following ways. The material: a) could be so highly hygroscopic that it would deny access of moisture to silica gel, b) could form a moisture repelling or impermeable coating over silica gel particles, c) could react chemically or form a solution with silica gel to change its nature, or d) could possess microscopic particles in the nanometer size range so that the capillary system inside the silica gel particles could be effectively plugged to prevent moisture adsorption. The experimental dust used to contaminate silica gel for the present experiment did not possess any of the above mentioned properties. The dust contained very fine particles, but the analysis of the dust particle sizes did not indicate presence of particles smaller than 5 micrometers, which was more than one thousand times the average diameter of the capillaries inside silica gel particles.

Dust particles reportedly found in agricultural operations are likely to be similar to or larger in size ranges than the experimental dust. The nature of airborne agricultural dust is not expected to be such that it can form impermeable coating on silica gel particles or react chemically with it. The results of the present experiments indicate that the equilibrium moisture content of silica gel is not likely to be affected by the presence of dust particles.

Dynamic Sorption Rates

The rate at which silica gel and air transferred moisture was a function of the difference between the vapor pressures inside silica gel and in the air (Hougen and Dodge, 1947). The rate of moisture exchange at any instant was a function of the moisture content of the silica gel and the relative humidity of the air. The relative humidity levels were kept constant for the present experiments, but the moisture content and the vapor pressure inside silica gel changed continuously during an experiment until hygroscopic equilibrium was established. This changing moisture transfer rate itself could not be a reliable indicator of the effect of the dust particles. Moreover, the inevitable variation in the initial moisture content of the experimental samples made the rate of moisture transfer different even for the samples treated at the same relative humidity. A method of comparing the sorption rate data not affected by the variations noted above had to be found.

One way of describing a phenomenon depending on various factors was to express the relationship of the factors in a mathematical model. A simple and useful mathematical model describing the dynamic process of moisture sorption by hygroscopic materials may be recalled from the review of literature. The model was:

$$MR = \exp{(-k\theta)} \qquad (3)$$

$$\text{Where:} \quad MR = (M-Me)/(Mo-Me) \qquad (3a)$$

The above model reduced the instantaneous moisture content data M to a non-dimensional moisture ratio MR and eliminated the initial moisture Mo and the final or equilibrium moisture Me in the process. The

dependent variable MR was expressed as a function of a single charac-
teristic parameter k and the time θ. The parameter k, called the
sorption constant or sorption index could describe the rate of moisture
sorption in terms of the rate of approach towards equilibrium. Data of
moisture content as a function of time could be fitted to the above
model by using a simple transformation for utilizing linear regression
techniques, so that:

$$Ln(MR) = -k\theta \tag{3b}$$

Data of the dynamic sorption experiments were successfully fitted
to the model (equation 3b) from the basic data shown in Appendix C.
The linear regression analyses for fitting the transformed data to the
linear model showed a general high correlation coefficient ($R^2 \geq 0.988$).
The null hypothesis of k=0 could be rejected in each case at a con-
fidence level of 99% or better (i.e. $\alpha \leq 0.01$), and the coefficient of
variation of the data points were generally in the rate of 2% to 10%.

After the computation of the value of k for a set of data, the
regression line representing the data set could be established, and the
mathematical model of equation 3b could be re-transformed to the
exponential form of equation 3. This re-transformation made it possible
to plot a prediction line for the moisture content data from the regres-
sion coefficient k and from the known values of the initial and equilib-
rium moisture contents of a particular sample of silica gel. Examples
of regression lines and moisture prediction lines for a desorption
experiment and an adsorption experiment are shown in Figures 6 and 7.
The agreements between the moisture content data points and the corres-
ponding points from the fitted exponential curve, as shown in Figure 6
and Figure 7, were similarly close in all cases. Differences between
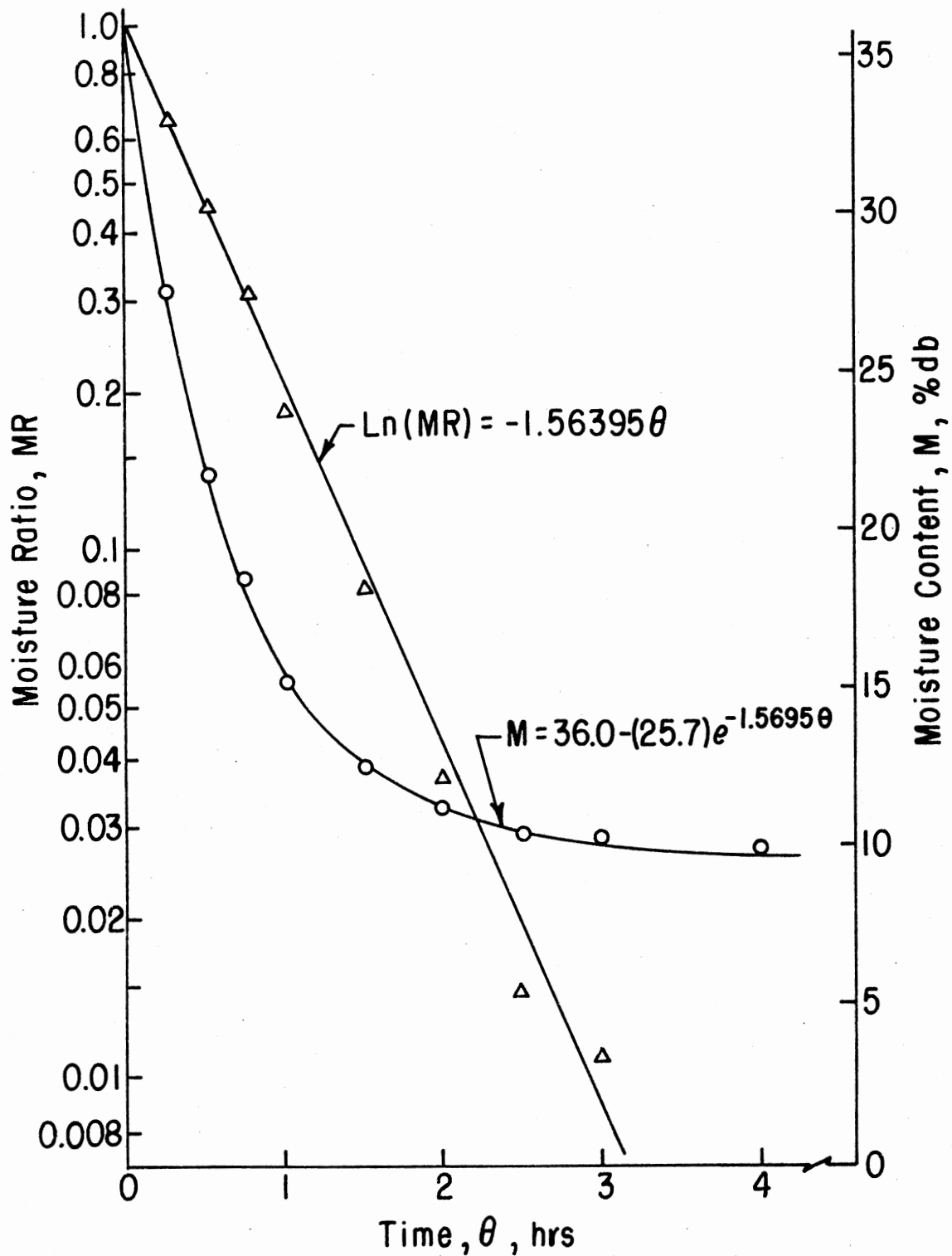
Figure 6.   An Example of Desorption Regression Line for
            Sorption Constant k, and Prediction Line
            for Moisture Content Calculated from k and
            Other Data (Mo=36.0, Me=10.3, RH=20%,
            Dust=0.0%)
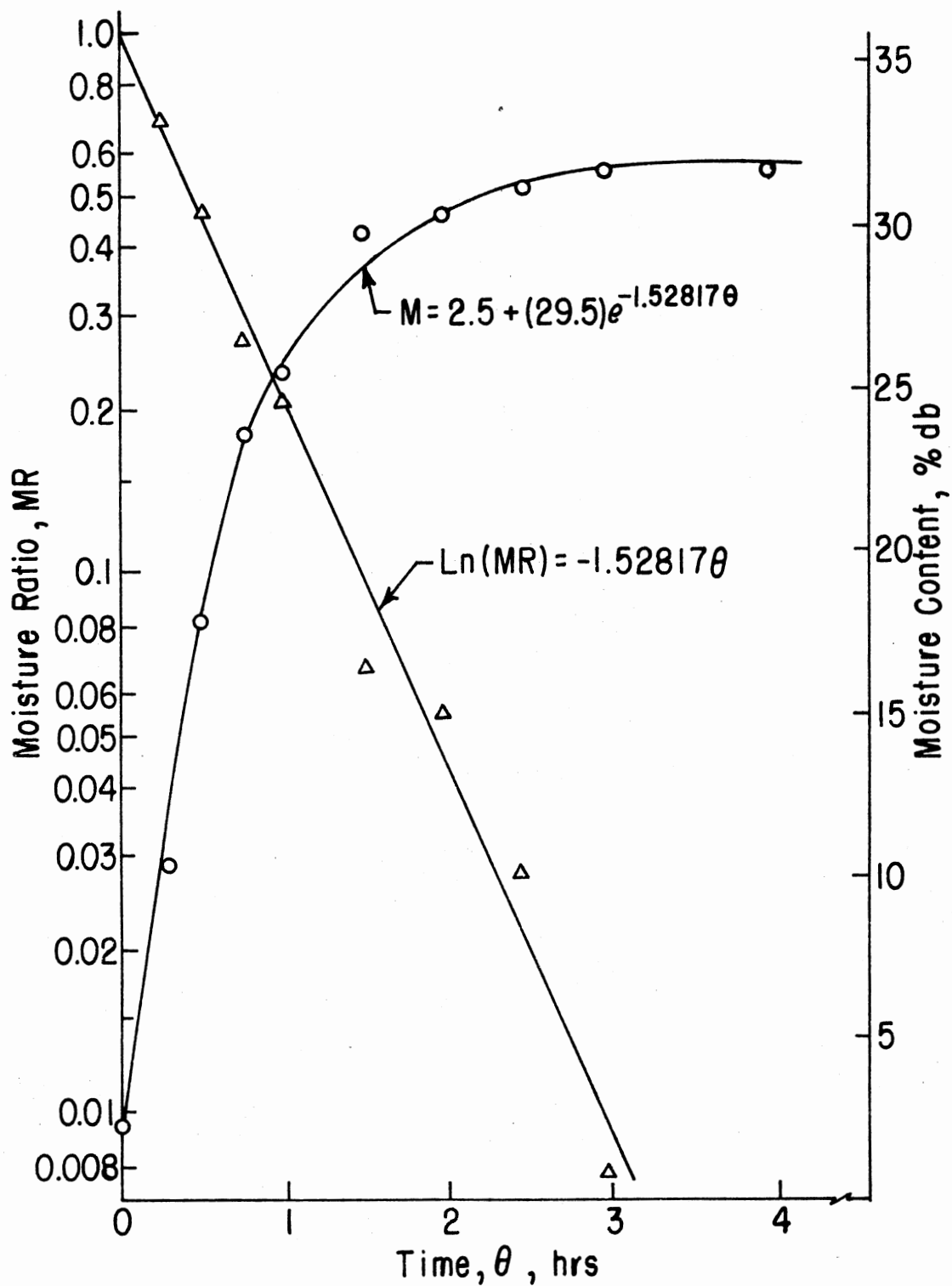
Figure 7. An Example of Adsorption Regression Line for
Sorption Constant k, and Prediction Line
for Moisture Content Calculated from k and
Other Data (Mo=2.5, Me=32.9, RH=60%,
Dust=0.0%)

experimental values of moisture content and the corresponding moisture content values from the fitted line were noticed to be not more than ± 2.5% moisture content (d.b.). The high correlation of the regression lines and the close agreement between the data and the fitted exponential lines were indicative of the appropriateness of the mathematical model chosen for describing the time dependent moisture content value of a fixed shallow bed of silica gel subjected to aeration at a constant dry bulb temperature, relative humidity, and airflow rate.

k Values from Grade 01 Silica Gel Experiments

All k values obtained from experiments with the grade 01 (3-8 Tyler mesh) silica gel are shown in Table VIII. It may be recalled from the description of the experimental methods that the sample sizes of silica gel were 150 grams, superficial airflow rate was 24 m/min, and the total airflow rate was 9.0 m^3/hr (320 SCFH) for this batch of experiments.

The values of the dynamic sorption constant k for this experimental batch were plotted in Figure 8 to show the effect of the dust content. The lower k values indicated slower rate of approach towards equilibrium. The value of k was affected by the dust content at all relative humidity levels and in both the adsorption and desorption processes. Increased dust content caused a reduction in the value of k, as shown in Figure 8, implying a reduced rate of moisture transfer.

k Values from Grade 05 Silica Gel Experiments

The values of adsorption constant 'k' obtained from experiments with grade 05 (6-16 Tyler mesh range) silica gel are shown in Table IX.

TABLE VIII

EXPERIMENTAL VALUES OF THE SORPTION CONSTANT
k FOR THE GRADE 01 SILICA GEL*

Relative Humidity	Sorption Condition	Dust Level (% by Weight)	Values of k (Hour^{-1}) for Three Replications**			Average k (Hour^{-1})
20%	Desorption	0	1.5122	1.5529	1.5639	1.5430
		2	1.3328	1.3294	1.3362	1.3328
		5	1.1932	1.1814	1.1160	1.1635
60%	Adsorption	0	1.5460	1.5706	1.5282	1.5483
		2	1.2828	1.2258	1.3131	1.2739
		5	1.1685	1.1258	1.1970	1.1638
75%	Adsorption	0	1.5180	1.5876	1.5042	1.5366
		2	1.3043	1.3025	1.3024	1.3031
		5	1.1846	1.2015	1.1724	1.1862
90%	Adsorption	0	1.5283	1.5680	1.5279	1.5414
		2	1.2512	1.3486	1.3409	1.3136
		5	1.1492	1.1581	1.1905	1.1659

*Constant Parameters:
 Nominal Size Range of Silica Gel = 3-8 Mesh, Tyler.
 Geometric Mean Particle Size of the Gel = 3.7 mm.
 Nominal Particle Size Range of the Dust Contaminant = 10-20 micro-
   meters.
 Superficial Airflow Rate = 24 m^3/m^2-min.

**Values of k found from statistical fitting of experimental data to
 the model MR=exp(-kθ). The correlation coefficients (R^2) for the
 linear regression analyses were 0.988 or higher in all cases.
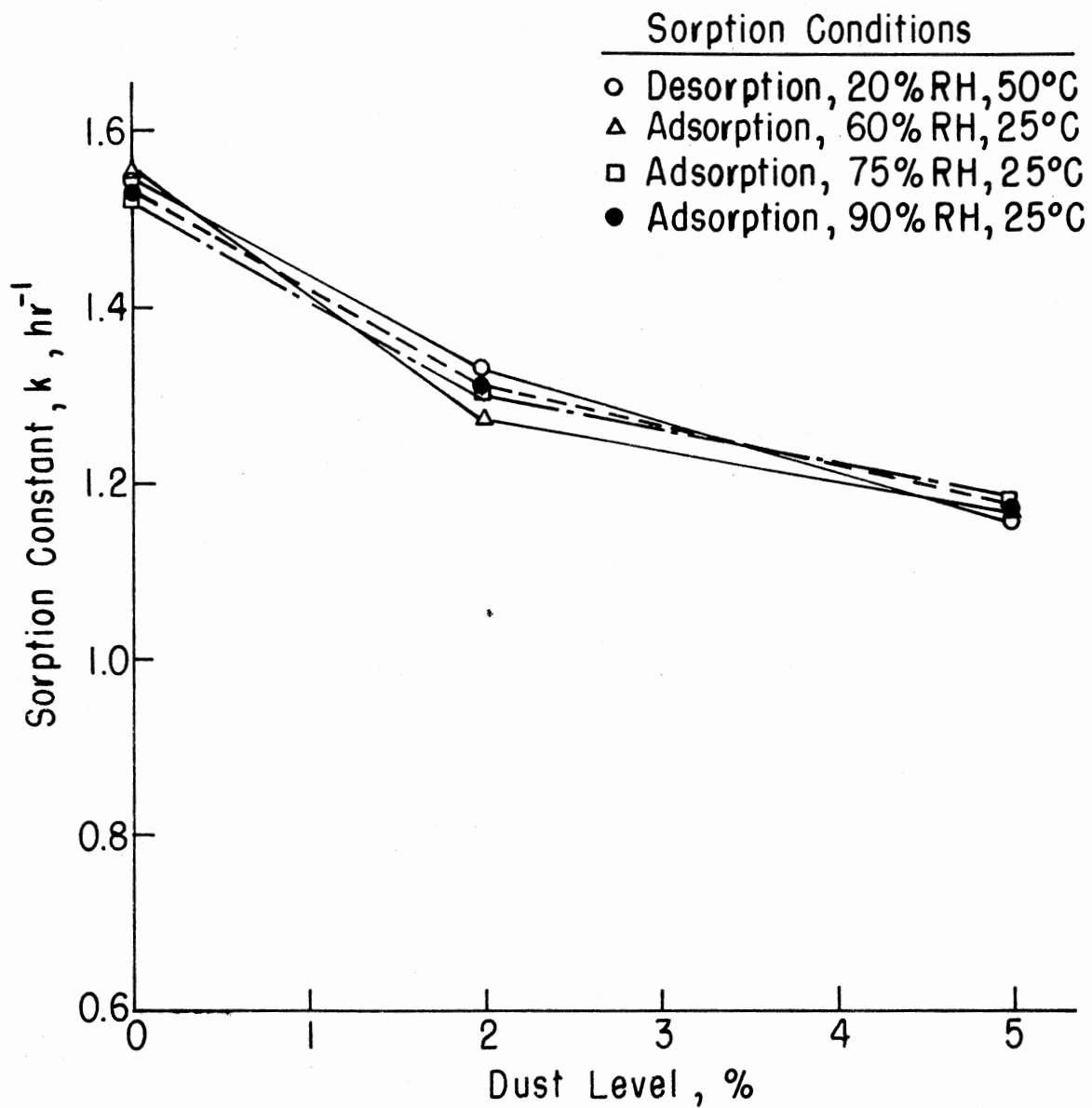
Figure 8.   Effect of Dust on Sorption Constant k from Experiments with Grade 01 (3-8 Mesh) Silica Gel; Data Averaged Over Three Replications

TABLE IX

EXPERIMENTAL VALUES OF THE SORPTION CONSTANT
k FOR THE GRADE 05 SILICA GEL*

Relative Humidity	Sorption Condition	Dust Level (% by Weight)	Values of k (Hour^{-1}) for Three Replications**			Average k (Hour^{-1})
20%	Desorption	0	1.7980	1.6257	1.7231	1.7156
		2	1.1171	1.1842	1.1439	1.1484
		5	0.9486	1.0551	0.9900	0.9979
60%	Adsorption	0	1.6017	1.7254	1.6297	1.6523
		2	1.1708	1.1904	1.1137	1.1583
		5	1.0147	1.0167	0.9790	1.0035
75%	Adsorption	0	1.6224	1.5774	1.5909	1.5969
		2	1.2550	1.2744	1.2738	1.2677
		5	0.8942	1.1301	1.1011	1.0418
90%	Adsorption	0	1.6292	1.5886	1.5885	1.6021
		2	1.3521	1.2780	1.3079	1.3127
		5	1.1564	0.9553	0.9921	1.0346

*Constant Parameters:
 Nominal Size Range of Silica Gel = 6-16 Mesh, Tyler.
 Geometric Mean Particle Size of Silica Gel = 1.8 mm.
 Nominal Particle Size Range of the Dust Contaminant = 10-20 micro-
   meters.
 Superficial Airflow Rate = 24 m^3/m^2-min.

**Values of k found from statistical fitting of experimental data to
 the model MR=exp(-kθ). The correlation coefficients (R^2) for the
 linear regression analyses were 0.990 or higher in all cases.

The sample size and aeration rates were the same as those used for grade 01 gel. The relative humidity levels (60, 75, and 90% at 25° C, and 20% at 50° C) and dust contamination levels (0, 2, and 5%) were also identical with those used for the grade 01 silica gel. The k values plotted for this batch of experiments are shown in Figure 9 which indicated the effect of dust content on the sorption constant k. The magnitude of k reduced with the increase of dust content. This indicated that with the increase in dust content, the rate of moisture transfer, and the rate of approach towards equilibrium condition slowed down. Consistent effect of any other factor was not readily evident from the data.

k Values from Grade 12 Silica Gel Experiments

The grade 12 (28-200 Tyler mesh) silica gel contained very fine particles as indicated by its mesh size range. The experimental sample size and the airflow rate for this batch of experiments had to be altered due to the fact that this finely ground silica gel offered comparatively higher resistance to airflow and tended to fluidize at relatively low airflow rates. A 75 gram sample size and 9 m/min super-ficial airflow rate, corresponding to a total airflow rate of 3.38 m^3/hr (120 SCFH) were used. The relative humidity and temperature of airflow and the dust contamination levels were the same as those used for the other two batches of experiments.

The results of k values from experiments with grade 12 silica gel are shown in Table X. The values of k for this batch were much lower than the corresponding values obtained with the other batches due to the lower airflow rate. The effect of dust content on the sorption
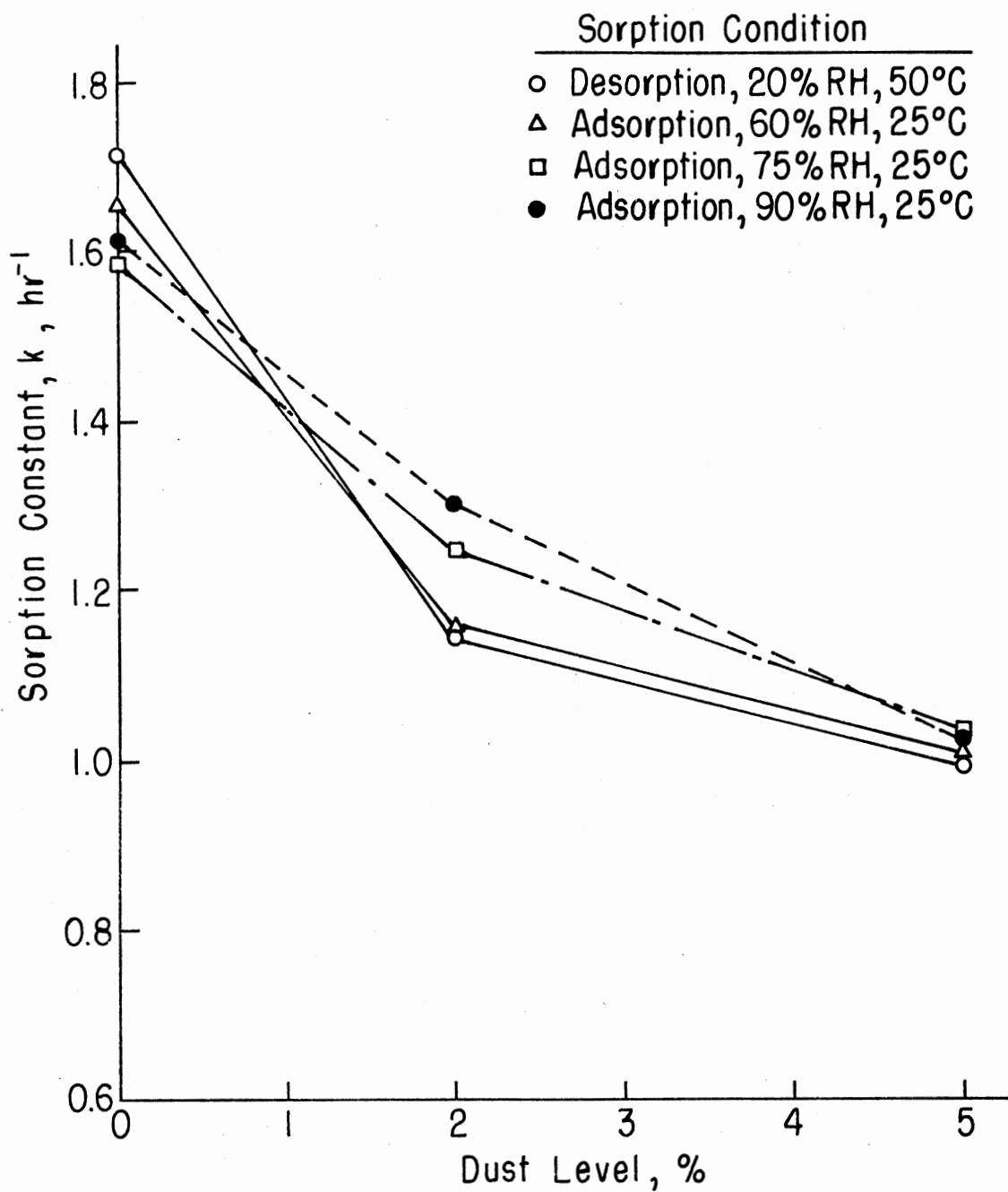
Figure 9.   Effect of Dust on Sorption Constant k from Experiments with Grade 05 (6-16 Mesh) Silica Gel; Data Averaged Over Three Replications

TABLE X

EXPERIMENTAL VALUES OF THE SORPTION CONSTANT
k FOR THE GRADE 12 SILICA GEL*

Relative Humidity	Sorption Condition	Dust Level (% by Weight)	Values of k (Hour^{-1}) for Three Replications**			Average k (Hour-1)
20%	Desorption	0	0.1699	0.1679	0.1706	0.1695
		2	0.1291	0.1298	0.1294	0.1294
		5	0.1007	0.1002	0.0999	0.1003
60%	Adsorption	0	0.1718	0.1711	0.1716	0.1715
		2	0.1297	0.1297	0.1299	0.1298
		5	0.1019	0.1042	0.1027	0.1029
75%	Adsorption	0	0.1693	0.1722	0.1756	0.1724
		2	0.1306	0.1328	0.1303	0.1312
		5	0.0996	0.1015	0.1001	0.1004
90%	Adsorption	0	0.1770	0.1654	0.1808	0.1744
		2	0.1304	0.1338	0.1270	0.1304
		5	0.0989	0.1036	0.1000	0.1008

*Constant Parameters:
 Nominal Size Range of Silica Gel = 28-200 Mesh, Tyler.
 Geometric Mean Particle Size of Silica Gel = 0.29 mm.
 Nominal Particle Size Range of the DUst Contaminant = 10-20 micro-
   meters.
 Superficial Airflow Rate = 9 m^3/m^2-min.

**Values of k found from statistical fitting of experimental data to the
 model MR=exp(kθ). The correlation coefficients (R^2) for the linear
 regression analyses were 0.997 or higher in all cases.

constant k was, nevertheless, similar to the effect observed with the other batches of experiments. The graphical representation of k on Figure 10 indicated that the increase of dust content caused a reduction of the sorption constant k, implying slowing down of the rate of approach towards equilibrium condtion.

Statistical Analyses for the Effects of
Dust and RH

The results of the dynamic sorption rate experiments with the three particle size ranges of silica gel, as described above, indicated a common trend regarding the effect of dust contamination on the sorption constant k; increase of dust was associated with a decrease of the k value. The effects of the other variables, if any, were not readily descernible from the casual comparison of the data. Statistical analyses of variance were performed with the data to determine the significances of the apparent effects.

The analysis of variance of the values of k obtained from experiments with grade 01 silica gel is shown in Table XI. The significances of the relative humidity, dust level, and the interaction of these two factors were tested. A null hypothesis of no effect could not be rejected for either relative humidity or its interaction with dust. But in case of the dust alone, the null hypothesis could be rejected at a very high confidence level, corresponding to a very low ($\alpha=0.0001$) probability of Type I error. Since the other factor, relative humidity, and interaction were not found significant, averages over all relative humidity levels at each dust contamination level could be computed. The average k values and the corresponding straight lines illustrating the
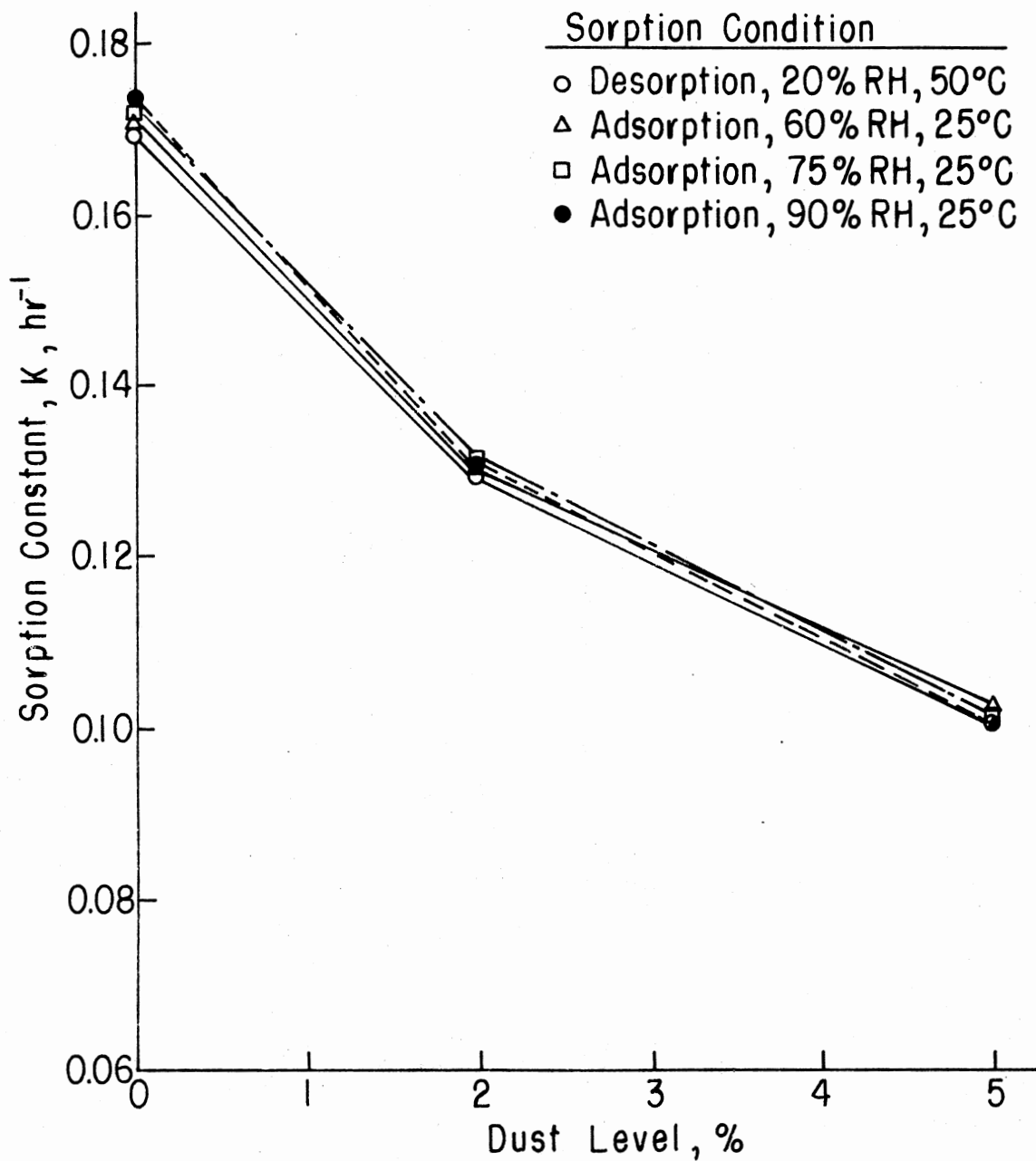
Figure 10. Effect of Dust on Sorption Constant k from Experi-
ments with Grade 12 (28-200 Mesh) Silica Gel;
Data Averaged Over Three Replications

sorption model $Ln(MR)=exp(-k\theta)$ for the grade 01 silica gel experiments are shown in Figure 11. Since the F ratio statistic in Table XI was found significant for the dust factor, a computation of the least significant difference (LSD) of the mean k values at the different dust levels was made. The computed value of LSD for mean k was 0.0342 at $\alpha=0.01$. The differences among mean k values at 0, 2, and 5% dust levels were much higher than the LSD. The F test and the comparison of the differences of mean k with LSD added statistical confidence to the previously observed effect of dust contamination on the dynamic sorption constant k.

The variances of the values of k from the grade 05 silica gel experiments are shown in Table XII. Dust factor was found highly significant ($\alpha=0.0001$). Relative humidity was not found significant, but the interaction of relative humidity and dust level was found significant at 5% level. Looking back at the data in Table IX and in Figure 9, it was apparent that the dust content level affected k in slightly different magnitudes at the different relative humidity levels. The computed significance level of the RH x Dust interaction ($\alpha=0.0153$) was much weaker than the significance level of the dust factor alone ($\alpha=0.0001$), and the apparent interaction might be due to the random error occurring during the experiments. Since the magnitude of the error sum of squares as shown in Table XII was low, and the difference among replications were also very low, and F ratio showing no significance at $\alpha=0.01$ could be ignored. If $\alpha=0.01$ was taken as the minimum criteria of testing significance for this experiment, the interaction of RH x Dust could be rejected. Considering the relative magnitude of the mean squares of the sources of variance, and the chosen criteria

TABLE XI

ANALYSIS OF VARIANCE OF THE SORPTION CONSTANT
k FOR THE GRADE 01 SILICA GEL

Source	Degrees of Freedom	Sum of Squares	F Ratio	Significance Level*
Corrected Total	35	0.88398		
RH	3	0.00155	0.50	0.68
Dust	2	0.85259	414.78	0.0001
RH x Dust	6	0.00517	0.84	0.55
Error-Rep (RH x Dust)	24	0.02467		

*Probability of error in rejecting a null hypothesis of no significance of the source of variation.

TABLE XII

ANALYSIS OF VARIANCE OF THE SORPTION CONSTANT
k FOR THE GRADE 05 SILICA GEL

Source	Degrees of Freedom	Sum of Squares	F Ratio	Significance Level*
Corrected Total	35	2.60590		
RH	3	0.01016	0.84	0.48
Dust	2	2.41806	300.12	0.0001
RH x Dust	6	0.08100	3.35	0.0153
Error-Rep (RH x Dust)	24	0.09668		

*Probability of error in rejecting a null hypothesis of no significance of the source of variation.
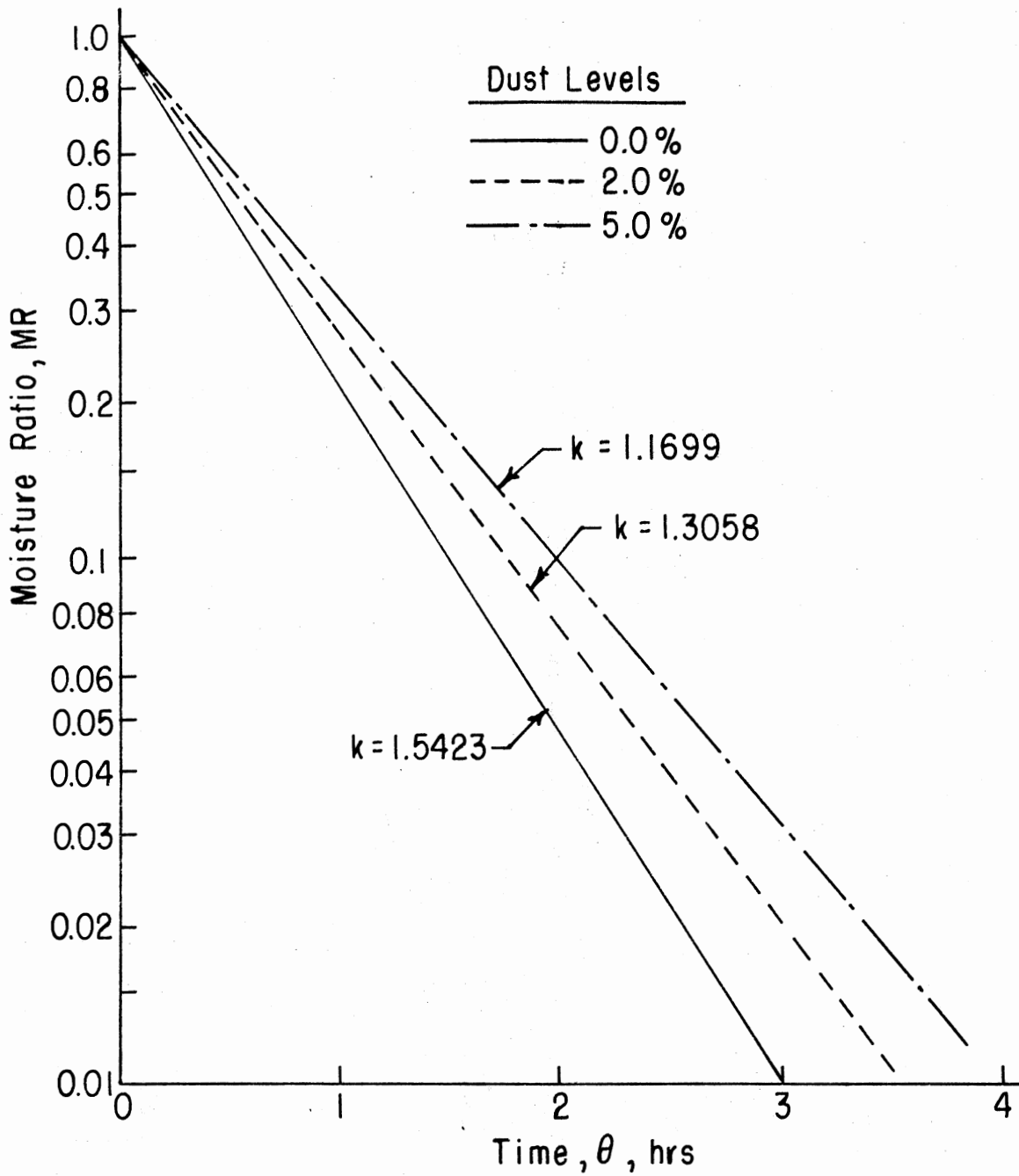
Figure 11. Moisture Ratio Versus Elapsed Time for Grade 01
Silica Gel Showing k Values Averaged Over RH
Levels (Computed LSD for k Was 0.0343 at
$\alpha=0.01$; Airflow=24 m/min)

of significance level, the RH x Dust interaction was not considered to be significant.

Averages of k values for the three dust levels over the other factors were computed and the LSD values for the average k values were computed. Comparison of the differences of the mean k values with the LSD (at $\alpha=0.01$) further indicated the significance of the significance of dust levels as a source of variation of the sorption constant k. The average k values and the corresponding moisture ratio lines are shown in Figure 12 for comparison.

Analysis of variance of the k values from experiments with grade 12 silica gel again indicated conclusions similar to those made in cases of the other two batches of experiments. Table XIII shows the analysis. Dust factor was found to be the only significant factor ($\alpha=0.0001$), whereas the relative humidity and the interaction of relative humidity with dust were not found significant even at the 90% confidence level ($\alpha=0.1$). The mean values of the sorption constant k were computed along with the least significant difference ($\alpha=0.1$). The mean values of the sorption constant k were computed along with the least significant difference (LSD, at $\alpha=0.01$). The results were graphically shown in Figure 13. The comparison of LSD with the mean k values, and the significance of the F ratio for the dust factor indicated that the dust contamination levels significantly affected the dynamic moisture sorption constant k.

Analysis of the Effect of Particle Size

The results of k values found from the experiments with the grade 01 and the grade 05 silica gel indicated that the values of k for the
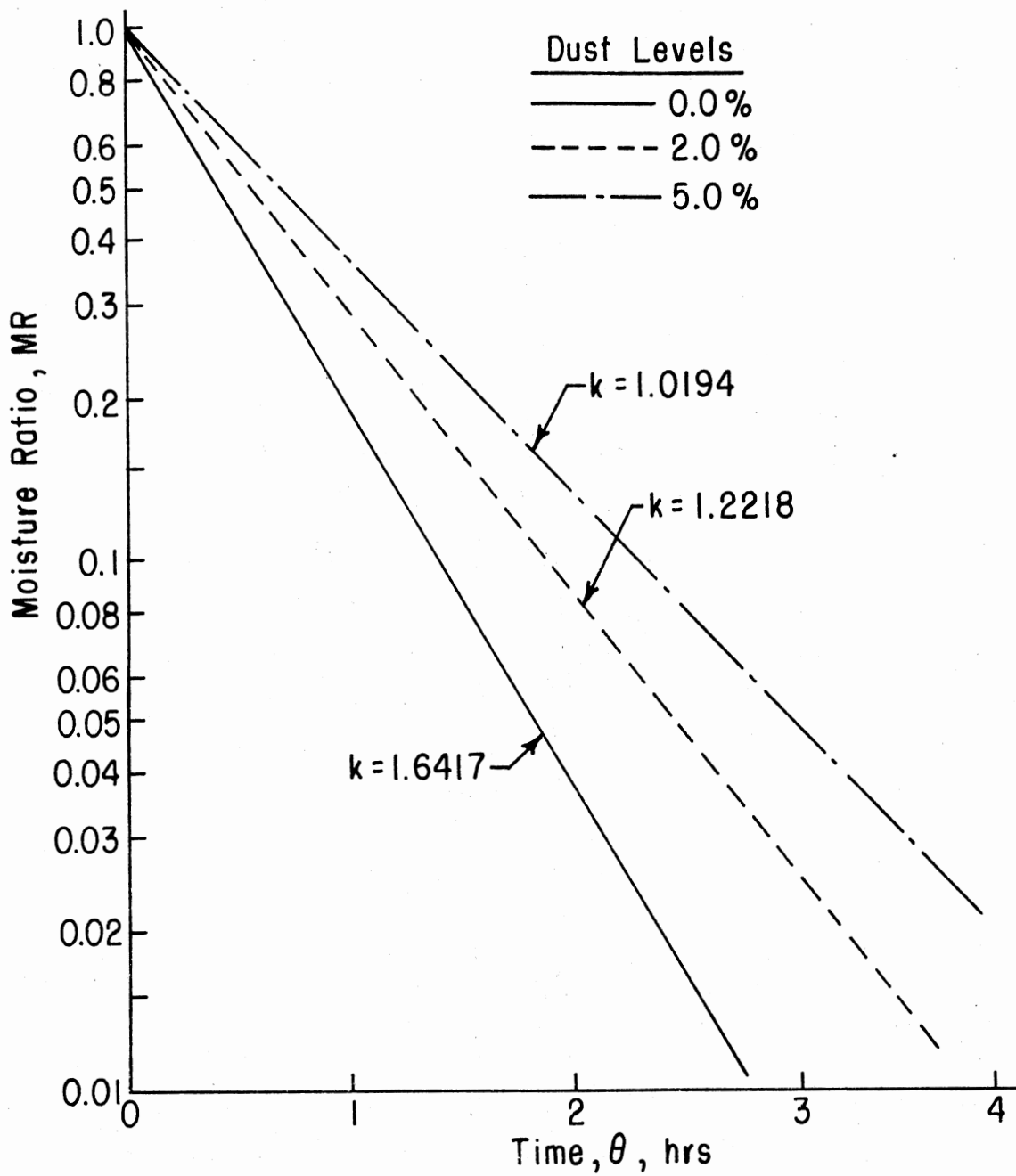
Figure 12.   Moisture Ratio Versus Elapsed Time for Grade 05
Silica Gel Showing k Values Averaged Over RH
Levels (Computed LSD for k Was 0.0838 at
$\alpha=0.01$; Airflow=24 m/min)

TABLE XIII

ANALYSIS OF VARIANCE OF THE SORPTION CONSTANT
k FOR THE GRADE 12 SILICA GEL

Source	Degree of Freedom	Sum of Squares	F Ratio	Level of Significance*
Corrected Total	35	0.03066		
RH	3	0.00002	0.97	0.42
Dust	2	0.03041	1852.45	0.0001
RH x Dust	6	0.00003	0.67	0.67
Error-Rep (RH x Dust)	24	0.00020		

*Probability of error in rejecting a null hypothesis of no significant effect of the source of variation.

TABLE XIV

ANALYSIS OF VARIANCE OF THE SORPTION CONSTANT
k FOR THE COMBINED DATA OF GRADE 01
AND GRADE 05 SILICA GEL

Source	Degree of Freedom	Sum of Squares	F Ratio	Level of Significance*
Corrected Total	71	3.52637		
Gel	1	0.03649	14.43	0.0004
RH	3	0.00799	1.05	0.38
Dust	2	3.06972	607.11	0.0001
Gel x RH	3	0.00372	0.49	0.69
Gel x Dust	2	0.20093	39.74	0.0001
RH x Dust	6	0.04565	3.01	0.014
Gel x RH x Dust	6	0.04052	2.67	0.026
Error-Rep (Gel RH Dust)	48	0.12135		

*Probability of error in rejecting a null hypothesis of no significance of the source of variation.
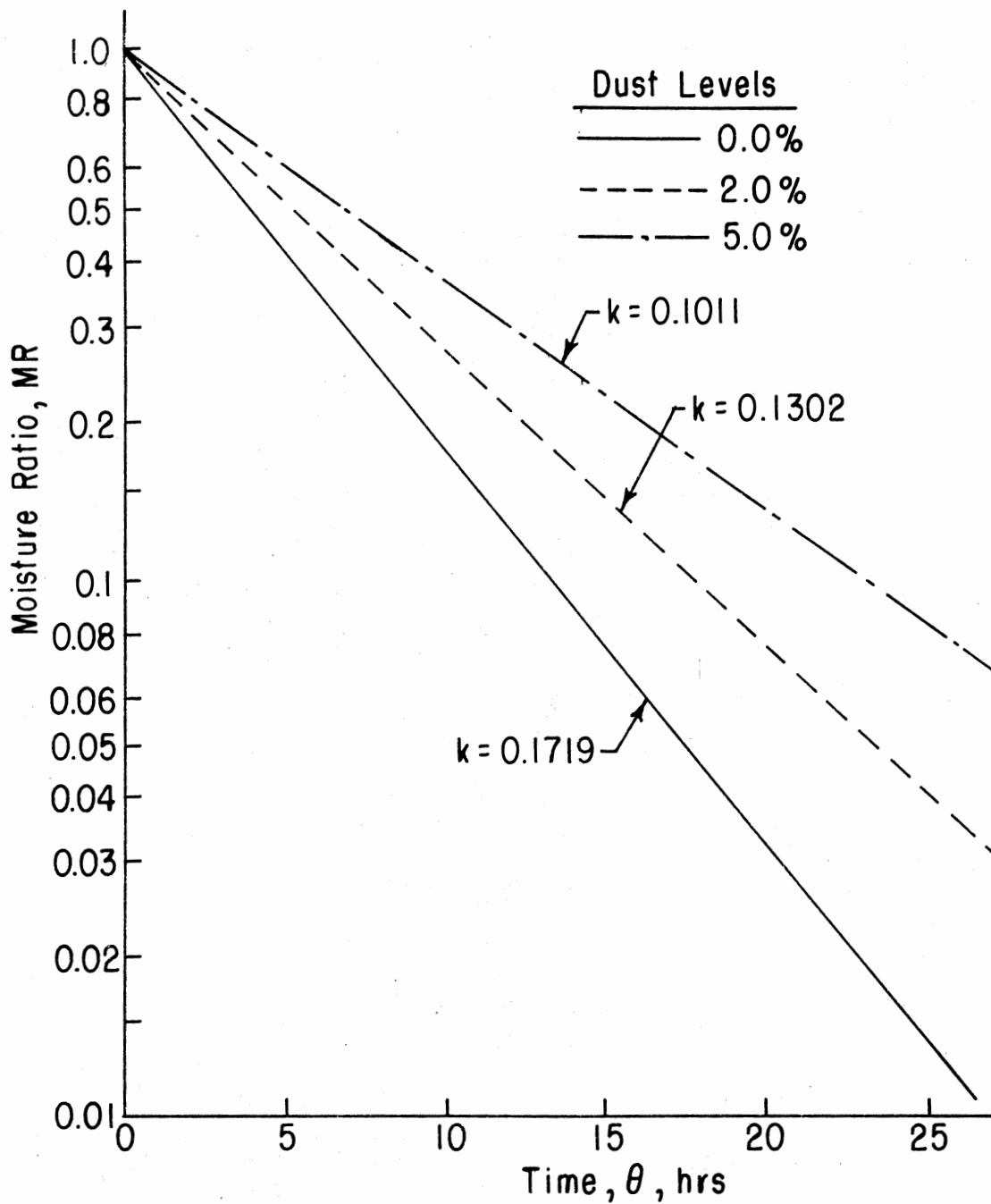
Figure 13. Moisture Ratio Versus Elapsed Time for Grade 12
Silica Gel Showing k Values Averaged Over RH
Levels (Computed LSD for k Was 0.0032 at
$\alpha=0.01$; Airflow=9 m/min)

grade 01 gel were generally slightly lower than the k values from grade of silica gel at zero dust level. Since the only difference between these two batches of experiments was the particle size ranges of the silica gel, the difference in k could be attributed to this factor. Published data from Ahlberg (1939) showed that smaller particle size of silica gel caused slightly faster moisture sorption than larger particle sizes when other factors were constant. The grade 01 silica gel had mesh size range of 3 to 8 Tyler mesh and a mean particle size of 3.67 mm, and the grade 05 silica gel had the mesh size range of 6 to 16 Tyler mesh with a mean particle diameter of 1.81 mm (see Table XVI in Appendix A). The present experimental results appeared to confirm that the finer particles of silica gel caused higher k values and approached equilibrium conditions at a slightly faster rate when dust contamination was absent.

The above trend reversed itself when dust was present. The average k values of dust contaminated and larger particle sized grade 01 silica gel were slightly higher than the corresponding values from grade 05 silica gel, as the comparison of Figures 12 and 13 indicated.

A statistical analysis for the confirmation of the above apparent effect of the particle size of silica gel and its interaction with dust contamination level could not be done in an unbiased way because of the design of experiments used in this research. Due to the practical limitations of equipment and facilities, the experiments could not be randomized with respect to the grades of silica gel used. Silica gel of the three different particle size ranges were experimented with separately as separate batches. The experiments with grade 01 and grade 05 silica gel were conducted at identical levels of the

variables except for the difference in their particle sizes associated with the grade designation. Lack of randomization with respect to this grade designation and introduction of a time confounding could make a common analysis of variance open to question.

If, however, it could be assumed that the time confounding was insignificant for such experiments conducted inside controlled environment chamber, and that the random errors were homogeneous for both the batches of experiments, some inference could be drawn from the analysis of variance.

A combined analysis pooling data from both grade 01 and grade 05 batches of experiments was done and it was shown in Table XIV. The significance levels were high for the effect of silica gel type ($\alpha=0.0001$) and for the interaction effect of silica gel type and dust level ($\alpha=0.0001$). The other factors and interactions did not indicate low enough value of the probability of Type I error to be called significant in the present context. It could be tentatively concluded that the particle size and its interaction with dust contamination were significant for the rate of moisture sorption by silica gel.

Contamination Factor

The preceding analysis of the experimental results had established that the rates of moisture adsorption and desorption, as indicated by the magnitude of the dynamic sorption constant k, were significantly affected by the dust contamination levels. The higher dust contamination level was associated with lower k value and slower rate of approach to equilibrium when other factors remained constant. The relative magnitude of the effect of dust contamination levels on the value of k

could be discerned by introducing a factor termed dust contamination factor, f_d, as defined below.

$$f_d = (k_d)/(k) \qquad (14)$$
$$\text{or } k_d = (f_d)\ (k) \qquad (15)$$

where:

k = sorption constant for uncontaminated silica gel for a particular combination of RH, Temp., and airflow rate.

k_d = sorption constant for dust contaminated silica gel for otherwise identical combination of variables as above.

f_d = dust contamination factor, fraction.

The calculated values of the dust contamination factors for the experimental results shown in Table XV, and the relationship of the contamination factors with dust levels shown in Figure 14 indicate the decrease of the value of f_d with the increase of dust contamination. The apparent relationship between the magnitude of f_d with the level of dust was non-linear; the value of f_d reduced at a diminished rate with the increase of dust level.

Application of Dust Contamination Factor

It had been demonstrated previously that the overall effect of dust contamination on the rate of moisture sorption could be expressed as a factor f_d which modified the value of the sorption constant k. The exponential model, and its transformed linear version could describe the moisture sorption phenomenon equally well for both uncontaminated and
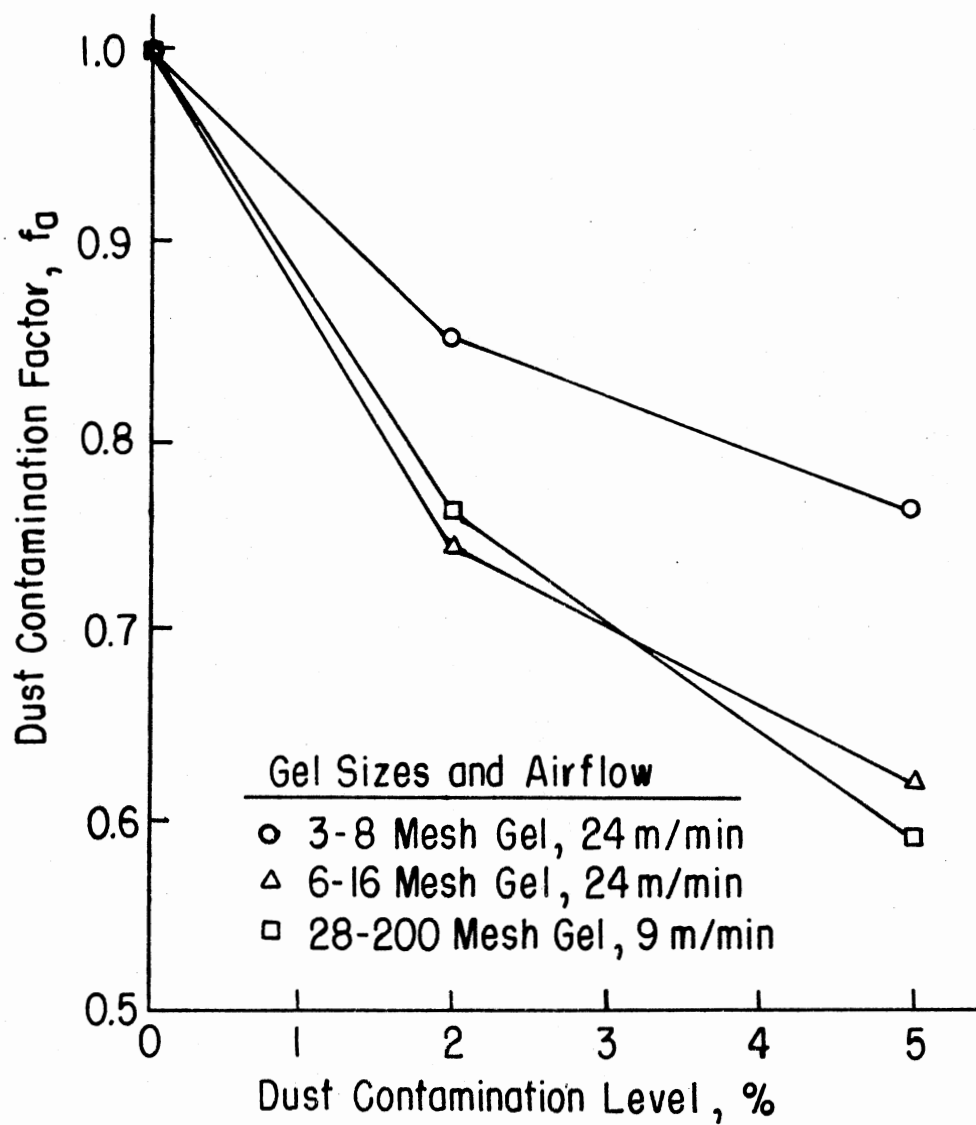
Figure 14.   Effects of Dust, Silica Gel Particle Size,
            and Airflow on Contamination Factor
            (Airflow=24 m^3/m^2-min. for 3-8 Mesh and
            6-16 Mesh Gel, 9 m^3/m^2-min. for 28-200
            Mesh Gel)

contaminated silica gel when the appropriate contamination factor was applied.

TABLE XV

DUST CONTAMINATION FACTORS

Silica Gel Mesh Size	Nominal Airflow Rate m^3/m^2 min	Dust Level, %	k, Averaged Overall RH Hr^{-1}	f_d
3-8	24	0	1.54232	1.0
		2	1.30584	0.85
		5	1.16985	0.76
6-16	24	0	1.64172	1.0
		2	1.22178	0.74
		5	1.01944	0.62
28-200	9	0	0.17193	1.0
		2	0.13024	0.76
		5	0.10111	0.59

The sorption constant k was an indicator of the moisture sorption rate of silica gel for a complete sorption period, and the value of k and its modifying factor f_d were found empirically. Similar empirical modifying factors are common for the design and analysis of heat transfer equipment. The effects of scale and contamination on heat transfer surfaces are often expressed in terms of a "fouling factor" modifying the heat transfer rate. The effects of such fouling are well known and discussed in common literature like Chemical Engineers' Handbook (Perry and Chilton, 1973), and it is sometimes represented as added resistance

against transfer of heat in analogous electrical circuits representing heat transfer phenomenon. Similarly, the dust contaminant may be seen as an added resistance against transfer of moisture, and equivalent electrical circuits may be drawn to represent moisture sorption by silica gel in presence of dust, as shown in Appendix B.

The factor f_d obviated the necessity of finding the different k values for the different levels of dust contamination. Any known k value for a particular airflow and gel particle size combination can be modified by f_d when contamination level is known.

The dust contamination factor can conceivably be used in all types of governing equations describing mass transfer at a solid surface. The basic differential equation used in the present work may be recalled here.

$$dM/d\theta = k(M-Me) \qquad (2)$$

The equation could be modified for taking dust contamination into effect in the following expression.

$$dM/d\theta = (f_d)k(M-Me) \qquad (2a)$$

The above would take the familiar form after solution using known boundary conditions.

$$MR = \exp(-f_d k\theta) \qquad (3c)$$

$$\text{and } Ln(MR) = -(f_d)k\theta \qquad (3d)$$

The contamination factor f_d can be used in other differential equations which utilize mass transfer coefficients. In the present research f_d modified k for dust contamination when all other pertinent factors, temperature, relative humidity, airflow rate, silica gel surface area, and particle diameter were constant. Other governing equations which

utilize mass transfer coefficient must take care of any effect of dust contamination by modifying the mass transfer coefficient when other factors remain constant, so that:

$$h_{md} = f_d h_m \tag{16}$$

where:

h_{md} = mass transfer coefficient for dusty surface.

h_m = mass transfer coefficient for dust free surface.

f_d = dust contamination factor.

The factor f_d, as operationally defined in equations 2a, 14, and 16, had successfully taken account of the effect of dust on the rate of moisture sorption and it can be hypothesized here that the same contamination factor can effectively account for the effect of dust in any other governing equation describing the phenomena of moisture sorption by silica gel.

Practical application of desiccant in large scale air drying operations and the subsequent regeneration of solid granular desiccants like silica gel involves thick columns of desiccant. Solution of predicting the behavior of such thick column has been successfully done by many, including Koh (1977) by using numerical iterative methods based on a basic differential equation for an elemental section of the desiccant column. Presence of dust contaminant in such a thick column has to be taken care of in the basic equation of mass transfer for prediction purposes. The dust contamination factor is expected to be a useful tool for this purpose.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Effects of contamination by fine dust particles in the size range of 10 to 20 micrometers on the equilibrium moisture content and on the rate of moisture adsorption and desorption by silica gel were investigated. Commercially available silica gel in three particle size ranges, 3-8, 6-16, and 28-200 Tyler mesh were used. Combinations of three relative humidity levels, 65, 75, and 90% at 25° C and one relative humidity level, 20% at 50° C, and three dust contamination levels, zero, two, and five percent by weight, for each of the three types of silica gel were used for the experimental investigation. The rates of airflow through fixed shallow beds of experimental silica gel used for finding the rates of adsorption and desorption by silica gel for the combinations of other variables were 24 m/min superficial air velocity for the 3-8 mesh and the 6-16 mesh silica gel and 9 m/min for the fine grained 28-200 mesh silica gel. The data of the change of moisture content in silica gel with the elapsed time of aeration were fitted to an exponential model and a dynamic moisture sorption constant k was determined. The effect of dust contamination on the sorption constant k was expressed as a dust contamination factor.

Conclusions

The equilibrium moisture content of silica gel at the four relative humidity levels investigated -- 60, 75, and 90% at 25° C, and 20% at 50° C -- were not discernibly affected by the presence of fine dust contaminants up to the level of 5% by weight. The amount of moisture adsorbed or desorbed by the silica gel particles to attain equilibrium with air at a fixed relative humidity and temperature remained unaffected by dust particles.

The experimental silica dust (10 to 20 micrometer in size) was found to be slightly hygroscopic, approximately one twentieth as hygroscopic as the activated silica gel. The average moisture content of dust contaminated silica gel at equilibrium was less than the moisture content of silica gel alone if the added mass of dust was considered, but the amount of moisture contained in the silica gel portion was not affected by the contaminating dust. The results of the equilibrium moisture tests were within $\pm$ 1.5% moisture content of the published results.

The dynamic processes of moisture adsorption and desorption by silica gel when subjected to aeration with air at a fixed temperature and relative humidity were found to be affected by the dust contaminant. The time dependent data of moisture content of silica gel were fitted to an exponential equation in which the sorption constant k indicated the dynamic sorption rate. The regression analysis for fitting the data showed high correlation coefficient ($R^2 \geq 0.988$) and low coefficient of variation (C.V.$\leq$10%). Analyses of variance of the computed values of k showed that dust was highly significant (α=0.0001) factor for all the

three size grades of silica gel.

The dust was found to affect the smaller grained (6-16 mesh) silica gel slightly more than the coarser grained (3-8 mesh) silica gel when other factors were identical.

Relative humidity and its interaction with dust content were found to be a significant factor ($\alpha=0.05$) for the value of the dynamic sorption constant k.

The effect of dust on the sorption constant was expressed in terms of a contamination factor f_d. The contamination factor was found dependent upon dust level and on the interaction of dust level and silica gel particle size grade. The contamination factor decreased with the increase of dust level, and it was smaller for finer grade silica gel than for coarser grade gel when the other variables were constant. Smaller values of contamination factor indicated slower rates of approach towards hygroscopic equilibrium with the environment. The decrease of the value of contamination factor with the increase of dust contamination level was apparently non-linear; the rate of decrease of the value of f_d appeared to fall with the increase of dust.

Recommendations for Future Work

Dust contamination factors should be found for more levels of contaminations so that f_d may be found as a continuous function of contamination level. Several rates of airflow may also be used to find its effect on the contamination level. An extensive set of data collected from several levels of airflow rates, dust contamination, and silica gel particle sizes are expected to be readily useful for design and analysis of practical sorption systems utilizing silica gel in dust

contaminated environment. Use of more than one fixed level of relative humidity may not be necessary since relative humidity was not found to be a significant factor affecting dust contamination factor.

The hypothesis that the dust contamination factor can be used unaltered in any governing equation should be tested by using it in the governing equation of a deep bed sorption analysis and computer simulation similar to the works reported by Koh (1977).

LITERATURE CITED

1 ASAE. 1978. ASAE standard: ASAE S319. Agricultural Engineers Yearbook, 25th Edition. ASAE, St. Joseph, Michigan.

2 Ahlberg, J. 1939. Rates of water vapor adsorption from air by silica gel. Industrial and Engineering Chem. 31:988-992.

3 Avant, R. V., C. B. Parnell, and J. W. Sorenson. 1976. Analysis of cyclone separator collection performance for grain sorghum dust. ASAE Paper No. 76-3543, presented in Chicago, Illinois.

4 Azer, N. J., D. Chung, and H. K. Koh. 1979. Regeneration of silica gel by adiabatic desorption. International Journal of Heat and Mass Transfer. (Manuscript reportedly accepted for publication.)

5 Bakker-Arkema, F. W., W. G. Bickert, and R. J. Patterson. 1967. Simultaneous heat and mass transfer during the cooling of a deep bed of biological products under varying inlet air condition. J. of Agric. Engineering Research 12:297-308.

6 Bangladesh Agricultural Research Council. 1975. Workshop on Appropriate Agricultural Technology: Recommendations. Bangladesh Agricultural Research Council, Dacca, Bangladesh.

7 Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1974. Drying Cereal Grains. AVI Publishing Co., Inc., Newport, Connecticut.

8 Bullock, C. E., and J. L. Threlkeld. 1966. Dehumidification of moist air by adiabatic adsorption. Trans. ASHRAE 72:301-313.

9 Bundy, D. S. 1974. Ionization control and particle size distribution in swine buildings. Unpublished Ph.D. Thesis. Iowa State University.

10 Close, D. J., and P. J. Banks. 1972. Coupled equilibrium heat and single adsorbate transfer in fluid flow through a porous medium II: Prediction for a silica-gel air-drier using characteristic charts. Chemical Engineering Science 27:1157-1169.

11 Close, D. J., and R. V. Dunkle. 1977. Use of adsorbent beds for energy storage in drying of heating systems. Solar Energy 19: 233-238.

12 Duffie, N. A., and D. J. Close. 1978. The optimization of a solar timber drier using an adsorbent energy store. Solar Energy 20:405-411.

13 First, M. W. et al. 1974. Control of odors and aerosols from spent grain dryers. J. of Air Pollution Control Assoc. 24:653.

14 Grace, W. R. 1966. The Fluid Processing Handbook. Technical Service Dept., Davison Chemical Div., W. R. Grace & Co., Baltimore, Maryland.

15 Hamdy, M. Y., and h. J. Barre. 1970. Analysis and hybrid simulation of deep bed drying of grain. Trans. ASAE 13:752-757.

16 Henderson, S. M., and R. L. Perry. 1966. Agricultural Process Engineering. 2nd Edition. John Wiley & Sons, New York, New York.

17 Hougen, O. A., and F. W. Dodge. 1947. The Drying of Gases. J. W. Edwards. Ann Arbor, Michigan.

18 Hougen, O. A., and W. R. Marshall. 1947. Adsorption from a fluid stream flowing through a stationary granular bed. Chemical Engineering Progress 43:197-208.

19 Hougen, O. A., H. J. McCauley, and W. R. Marshall. 1940. Limitation of diffusion equation in drying. Trans. Am. Inst. Chem. Eng. 36:183-205.

20 Hubard, Stephen S. 1954. Equilibrium data for silica gel and water vapor. Industrial & Engineering Chem. 46:356-358.

21 Hukill, W. V. 1947. Basic principles of drying corn and grain sorghum. Agricultural Engineering 28:335-338, 340.

22 Jury, S. H., and H. R. Edwards. 1971. The silica gel - water vapor sorption therm. Canadian J. of Chem. Eng. 19:663-666.

23 Kmiec, Andrzej. 1975. Simultaneous heat and mass transfer in spouted beds. Canadian J. of Chem. Eng. 53:18-24.

24 Koh, H. K. 1977. Study on the use of solar energy for the regeneration of silica gel used for grain drying. Unpublished Ph.D. Thesis, Kansas State University.

25 Kotb, A. K., and J. M. Campbell. 1968. Regeneration temperature and pressure are some of the hidden factors affecting the life of silica gel in fixed bed units. Gas 44:55-56.

26 Ledoux, E. 1948. Avoiding destructive velocity through adsorbent beds. Chemical Engineering 55:118-119.

27 Luikov, A. V. 1966. Heat and Mass Transfer in Capillary Porous
        Bodies. London: Pergamon Press.

28 Martin, C. R., and L. E. Stephens. 1977. Broken corn and dust
        generated during repeated handling. Trans. ASAE 20:168-171.

29 Matlock, S. W., L. R. Wiederhold, and C. B. Parnell. 1976. Par-
        ticle sizing of dust found in cottonseed oil mills. Trans.
        ASAE 19:970-976.

30 Moore, Larry C. 1979. A comprehensive guide for measuring fluid
        contaminant with liquid automatic particle counter. Basic
        Fluid Power Research Journal 12:159-162.

31 Newman, A. B. 1931. The drying of porous solids: Diffusion and
        surface emission equations. Trans. Am. Inst. Chem. Eng. 27:
        203-310.

32 Odigboh, E. V. 1976. Dehumidified air from sorbent beds for
        aeration food grains. J. of Agric. Engineering Research 21:
        273-280.

33 Pearse, J. F., T. R. Oliver, and D. M. Newitt. 1949. The mechanism
        of the drying of solids, part I: The forces giving rise to
        movement of water in granular beds during drying. Trans.
        Inst. of Chem. Eng. (London) 27:1-18.

34 Perry, R. H., and C. H. Chilton. 1973. Chemical Engineers Hand-
        book. 25th Edition. McGraw Hill, New York, New York.

35 Snedecor, G. W., and W. G. Cochran. 1967. Statistical Methods.
        6th Edition. Iowa State University Press, Ames, Iowa.

36 Van Arsdel, W. B. 1947. Approximate diffusion calculations for
        the falling rate phase of drying. Chem. Eng. Progress 43:13-
        24.

APPENDIXES

APPENDIX A

PARTICLE SIZE AND PRESSURE DROP DATA

TABLE XVI

PARTICLE SIZE ANALYSIS OF SILICA GEL
USED IN EXPERIMENTS

Grade	Tyler Mesh Size Range	Geometric Mean Diameter* of Particles, mm	Geometric Standard Deviation* of Particle Size
01	3-8	3.67	1.23
05	6-16	1.81	1.39
12	28-200	0.287	2.04

*Definition of the terms and the method of determination followed from ASAE (1978).

TABLE XVII

PARTICLE SIZE DATA OF THE
EXPERIMENTAL DUST*

Diameter, Micrometer	Number of Particles Above Specified Diameter Counted in Test Sample		
	Count 1	Count 2	Count 3
5.0	9,290	9,393	9,267
10.0	8,722	8,814	8,697
12.5	7,323	7,394	7,322
15.0	5,205	5,325	5,230
17.5	3,322	3,328	3,348
20.0	1,808	1,837	1,877
22.5	1,081	1,113	1,105
25.0	559	570	572
30.0	200	184	209
35.0	63	59	61
40.0	20	25	25
50.0	6	6	3

*Particle sizes determined at the Fluid Power Research Center at OSU, using the method described by Moore (1979).
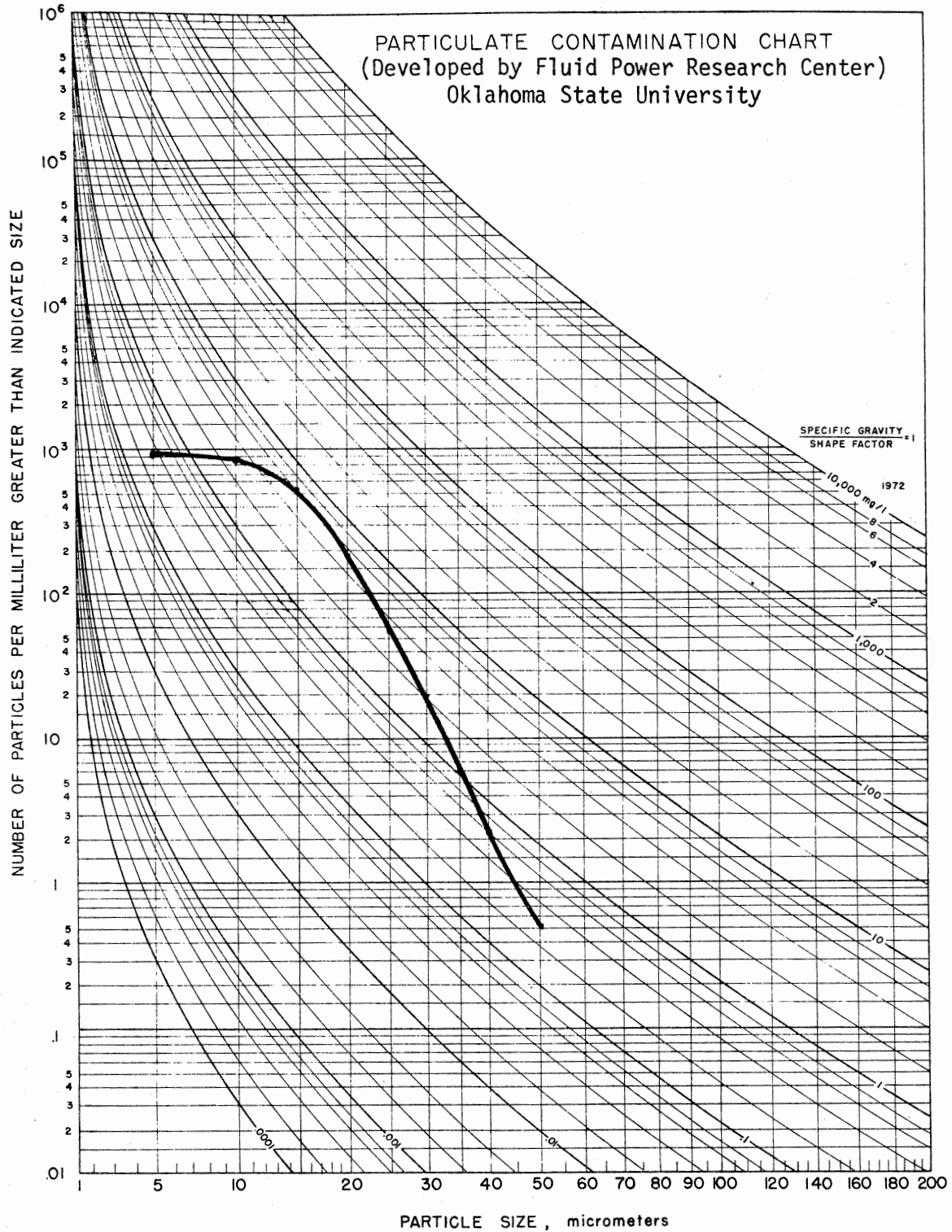
Figure 15. Particle Size Distribution of the Experimental Dust
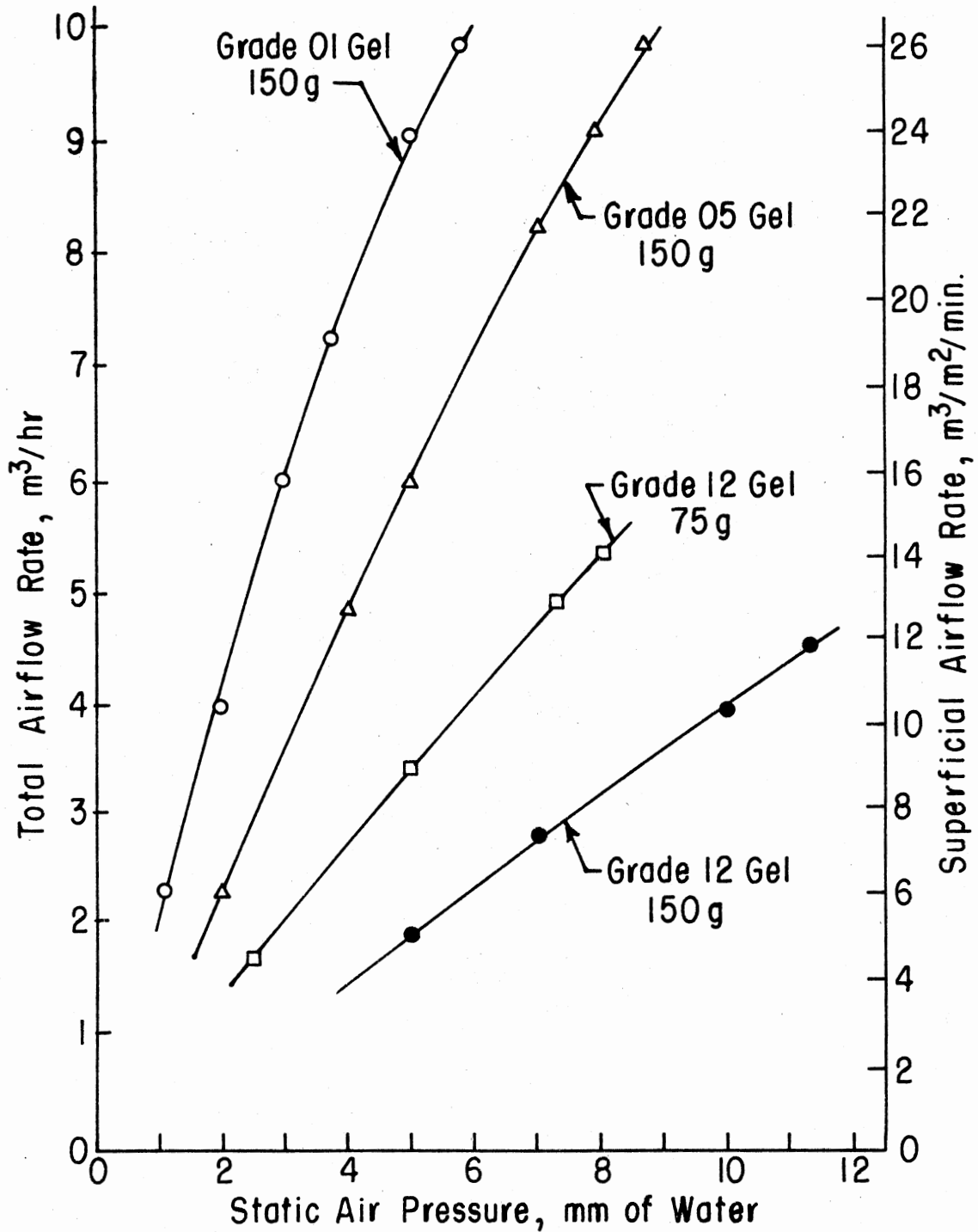
Figure 16. Airflow Versus Plenum Chamber Static Air
Pressure for Different Grades and Samples
Sizes of Silica Gel in Aeration Bins

APPENDIX B

ELECTRICAL CIRCUIT EQUIVALENT

FOR THE SORPTION PROCESS

ELECTRICAL CIRCUIT EQUIVALENT

FOR THE SORPTION PROCESS

The exponential model describing both adsorption and desorption
of the moisture by silica gel, and the observed effects of dust con-
tamination on the rate of sorption and on the absence of any effect
of dust on the final moisture content, suggest an analogy with the
charging and discharging of electrical capacitors. Electrical resistive-
capacitative (RC) circuits charge or discharge at a diminishing rate
until the steady state or equilibrium is established between the charged
electromotive force and the externally applied electromotive force. For
any fixed values of the initial charge and the external electromotive
force, the rate of approach to the steady state is governed by the
resistance in the circuit, but the final value of the charge is inde-
pendent of the value of the circuit resistance. The above behavior of
RC circuits is similar to the observed behavior of silica gel sorption
where the moisture is analogous to charge, vapor pressure difference
is analogous to difference in the electromotive force, resistances to
moisture transfer is analogous to resistance in electrical circuits,
and moisture holding capacity is analogous to the capacitance of elec-
trical capacitors.

The moisture sorption process of silica gel with a known initial
moisture content and subjected to aeration of a fixed relative humidity
may be simulated by the analogous equivalent electrical circuit shown in

Figure 17. The initial charge in the capacitor C appears as V_1 volts, and the capacitor is switched on to make a series circuit with a battery having V_2 volts through the resistancd R. The instantaneous
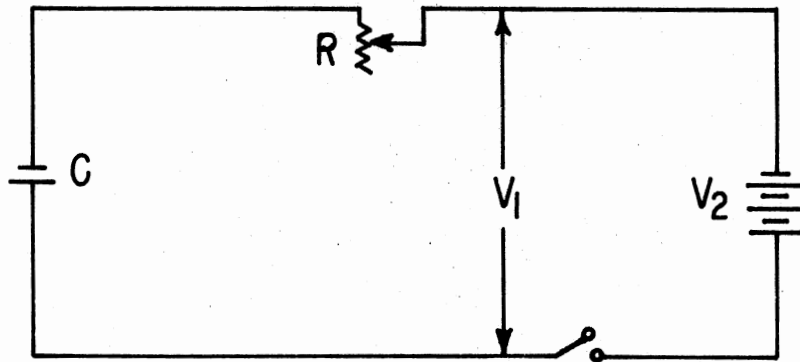
Figure 17. Equivalent Electrical Circuit
            for the Sorption by Silica
            Gel

voltage V across the capacitor appraoches the final value V_2 as per the following relationship after the switch is closed.

$$V = V_2 + (V_1 - V_2) \exp (-\theta/RC) \qquad (17)$$

$$\text{or} \quad (V - V_2)/(V_1 - V_2) = \exp (-\theta/RC) \qquad (17a)$$

This equation is comparable to the moisture sorption model used in equation 3.

$$(M - Me)/(Mo - Me) = \exp (-k\theta) \qquad (3)$$

The sorption constant k is evidently analogous to 1/RC, the inverse of time constant in RC circuits. If dust contamination is present, the modified sorption constant may be represented by a new value of

resistance as follows:

$$k = 1/RC \qquad (18)$$

$$f_d k = 1/R_2 C \qquad (19)$$

Dividing equation 19 by equation 18 yields:

$$f_d = R/R_2 \qquad (20)$$

$$R_2 = R/f_d \qquad (20a)$$

The equation 20a shows how the effect of dust contamination factor on the circuit resistance in the equivalent electrical circuit.

Equivalent electrical circuits for understanding heat transfer problems are common practice, but such equivalent circuits are rarely used in mass transfer problems. The equivalent RC circuit is demonstrated above to be effective in simulating the behavior of silica gel in moisture sorption process.

APPENDIX C

DYNAMIC MOISTURE SORPTION DATA

TABLE XVIII

DYNAMIC SORPTION DATA FOR GRADE 01 SILICA GEL*

-- GRADE=01 RH=20 PROCESS=DESORB DUST=0 ---					GRADE=01 RH=60 PROCESS=ADSORB DUST=0 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
1	0.00	36.00	35.92	36.00	1	0.00	2.30	2.30	2.30
2	0.25	27.51	27.42	27.60	2	0.25	11.90	11.69	11.39
3	0.50	22.00	22.06	21.91	3	0.50	18.61	18.62	18.00
4	0.75	18.23	18.20	18.50	4	0.75	23.00	24.01	23.82
5	1.00	15.30	15.25	15.10	5	1.00	25.88	26.55	25.73
6	1.50	12.72	12.63	12.51	6	1.50	29.32	30.51	30.00
7	2.00	11.41	11.38	11.26	7	2.00	30.31	30.57	30.42
8	2.50	10.68	10.68	10.67	8	2.50	31.52	30.90	31.15
9	3.00	10.58	10.59	10.59	9	3.00	31.77	31.84	31.78
10	4.00	10.35	10.36	10.36	10	4.00	31.92	31.93	31.92
11	6.00	10.30	10.32	10.28	11	6.00	32.08	32.02	31.96

- GRADE=01 RH=20 PROCESS=DESORB DUST=2 ---					GRADE=01 RH=60 PROCESS=ADSORB DUST=2 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
12	0.00	36.00	36.10	35.92	12	0.00	2.30	2.30	2.30
13	0.25	29.01	29.36	28.75	13	0.25	10.49	10.62	10.60
14	0.50	23.67	23.78	23.42	14	0.50	16.40	16.16	15.99
15	0.75	19.78	19.65	19.71	15	0.75	20.51	20.44	20.38
16	1.00	17.50	17.25	17.50	16	1.00	23.75	24.50	23.58
17	1.50	14.08	14.08	13.98	17	1.50	27.81	28.12	27.83
18	2.00	12.40	12.42	12.31	18	2.00	29.62	29.97	30.02
19	2.50	11.31	11.40	11.24	19	2.50	30.90	30.85	30.11
20	3.00	10.79	10.78	10.76	20	3.00	31.35	31.20	31.52
21	4.00	10.40	10.40	10.41	21	4.00	31.82	31.67	31.87
22	6.00	10.31	10.32	10.28	22	6.00	31.95	31.86	31.93

- GRADE=01 RH=20 PROCESS=DESORB DUST=5 ---					GRADE=01 RH=60 PROCESS=ADSORB DUST=5 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
23	0.00	36.00	36.00	35.80	23	0.00	2.30	2.30	2.30
24	0.25	30.01	30.00	30.00	24	0.25	10.01	10.08	11.42
25	0.50	24.08	24.70	24.21	25	0.50	15.48	15.55	15.63
26	0.75	20.54	20.41	20.50	26	0.75	19.80	20.06	20.42
27	1.00	18.55	18.48	18.40	27	1.00	23.50	22.99	23.38
28	1.50	14.65	14.51	14.52	28	1.50	27.00	27.01	27.50
29	2.00	12.99	12.90	13.12	29	2.00	29.36	28.99	29.11
30	2.50	11.50	11.55	11.24	30	2.50	30.38	30.04	30.18
31	3.00	10.98	11.01	10.95	31	3.00	31.12	30.86	31.33
32	4.00	10.52	10.54	10.51	32	4.00	31.70	31.69	31.74
33	6.00	10.32	10.33	10.29	33	6.00	32.00	31.88	32.11

TABLE XVIII (Continued)

- GRADE=01   RH=75   PROCESS=ADSORB   DUST=0 --- GRADE=01   RH=90   PROCESS=ADSORB   DUST=0 -

OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
1	0.00	2.20	2.20	2.20	1	0.00	2.00	2.00	2.00
2	0.25	13.40	12.98	13.00	2	0.25	13.55	13.07	13.58
3	0.50	19.75	19.50	20.07	3	0.50	21.80	21.73	21.24
4	0.75	26.05	25.01	26.24	4	0.75	28.10	27.51	27.31
5	1.00	29.16	29.18	30.23	5	1.00	30.55	31.12	30.18
6	1.50	33.21	32.95	33.23	6	1.50	34.00	34.51	33.94
7	2.00	34.00	34.34	34.38	7	2.00	35.72	36.14	36.00
8	2.50	35.47	35.27	35.30	8	2.50	37.31	37.30	37.19
9	3.00	35.81	35.74	35.70	9	3.00	37.50	37.55	37.54
10	4.00	36.00	36.00	36.01	10	4.00	37.82	37.83	37.82
11	6.00	36.08	36.00	36.08	11	6.00	37.98	38.02	37.82

- GRADE=01   RH=75   PROCESS=ADSORB   DUST=2 --- GRADE=01   RH=90   PROCESS=ADSORB   DUST=2 -

OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
12	0.00	2.20	2.20	2.20	12	0.00	2.00	2.00	2.00
13	0.25	11.65	12.01	11.76	13	0.25	11.80	12.00	11.92
14	0.50	19.00	19.20	19.33	14	0.50	19.60	19.73	19.66
15	0.75	23.15	22.90	22.98	15	0.75	23.72	24.10	23.65
16	1.00	26.72	27.53	26.99	16	1.00	29.00	29.21	28.62
17	1.50	32.04	32.00	32.28	17	1.50	32.80	33.01	32.48
18	2.00	33.60	34.00	33.64	18	2.00	35.11	35.22	34.80
19	2.50	34.60	34.67	34.61	19	2.50	36.05	35.99	35.90
20	3.00	35.52	35.51	35.47	20	3.00	36.90	37.00	36.88
21	4.00	35.90	35.87	35.90	21	4.00	37.69	37.66	37.70
22	6.00	35.94	36.04	35.83	22	6.00	38.00	37.99	38.11

- GRADE=01   RH=75   PROCESS=ADSORB   DUST=5 --- GRADE=01   RH=90   PROCESS=ADSORB   DUST=5 -

OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
23	0.00	2.00	2.00	2.00	23	0.00	2.20	2.20	2.20
24	0.25	10.52	10.31	10.48	24	0.25	11.00	11.00	10.91
25	0.50	17.40	17.30	17.54	25	0.50	17.25	17.20	17.29
26	0.75	22.50	22.12	22.87	26	0.75	23.31	23.09	24.02
27	1.00	25.05	24.97	25.64	27	1.00	25.84	25.11	26.04
28	1.50	30.00	29.14	30.52	28	1.50	31.75	31.17	31.95
29	2.00	33.05	33.42	33.19	29	2.00	34.00	34.08	34.17
30	2.50	34.50	34.55	34.48	30	2.50	35.52	34.50	34.45
31	3.00	35.01	35.18	35.08	31	3.00	36.90	36.92	36.90
32	4.00	35.81	35.82	35.74	32	4.00	37.55	37.65	37.55
33	6.00	35.98	36.10	35.94	33	6.00	37.55	37.90	37.84

*Three replications, A, B, C, of moisture content M against time, θ
(theta), shown here. Other relevant data are shown in Table VIII.

TABLE XIX

DYNAMIC SORPTION DATA FOR GRADE 05 SILICA GEL*

- GRADE=05 RH=20 PROCESS=DESORB DUST=0					GRADE=05 RH=60 PROCESS=ADSORB DUST=0 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
1	0.00	33.3659	33.0232	32.2008	1	0.00	3.0000	3.0000	3.0000
2	0.25	25.4160	25.8957	24.7307	2	0.25	11.0340	11.7207	11.3773
3	0.50	20.2075	21.1669	20.0704	3	0.50	15.4973	17.6947	18.1753
4	0.75	16.5752	16.7808	16.0269	4	0.75	20.3040	22.2953	21.3340
5	1.00	13.4912	13.9709	13.2856	5	1.00	23.6000	24.4240	24.0807
6	1.50	11.2296	11.9149	10.6813	6	1.50	27.5827	27.7200	27.2393
7	2.00	10.4757	10.8184	9.7904	7	2.00	29.0933	29.2993	29.1620
8	12.00	10.3387	10.7499	9.3792	8	3.00	31.0160	30.3293	29.5740
					9	5.00	.	.	30.6040
					10	20.00	32.0460	31.4967	.

- GRADE=05 RH=20 PROCESS=DESORB DUST=2					GRADE=05 RH=60 PROCESS=ADSORB DUST=2 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
9	0.00	33.0353	32.9009	32.3634	11	0.00	3.0000	3.0000	2.6647
10	0.25	26.9210	26.8539	26.0476	12	0.25	9.7993	10.0686	10.2422
11	0.50	22.2850	22.0834	21.5459	13	0.50	14.5791	14.7810	14.1986
12	0.75	19.3286	19.2614	18.6567	14	0.50	14.5791	14.7810	14.8691
13	1.00	16.1707	16.4395	15.7004	15	0.75	18.6183	18.6856	18.0208
14	1.50	14.3566	14.2222	13.7519	16	1.00	21.4458	21.5131	20.9714
15	2.00	12.2737	12.1393	11.6690	17	1.50	25.5523	25.4850	25.3301
16	3.00	10.9299	.	10.3252	18	2.00	27.3699	27.5719	26.9395
17	12.00	10.2580	10.0565	9.5861	19	3.00	27.9758	27.9085	27.2747
					20	6.00	.	28.1105	.

- GRADE=05 RH=20 PROCESS=DESORB DUST=5					GRADE=05 RH=60 PROCESS=ADSORB DUST=5 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
18	0.00	31.8451	31.3882	31.8451	21	0.00	3.0000	3.0000	3.0000
19	0.25	26.4930	26.1013	26.4277	22	0.25	10.2637	9.6747	9.9321
20	0.50	22.5115	22.7073	22.9684	23	0.50	14.5172	.	15.2946
21	0.75	19.9007	19.8354	20.0312	24	0.75	18.1817	18.0508	18.2375
22	1.00	17.0288	16.9636	17.0288	25	1.00	20.6029	20.1449	20.6571
23	1.50	13.7653	13.7001	13.8306	26	1.50	24.4638	24.5947	23.7308
24	2.00	12.3947	12.3294	12.2641	27	2.00	26.0343	26.1652	25.7581
25	12.00	9.9144	8.5437	8.4785	28	3.00	29.1099	29.1753	28.3086
					29	5.00	.	.	28.6356
					30	20.00	29.8952	30.2224	.

TABLE XIX (Continued)

GRADE=05 RH=75 PROCESS=ADSORB DUST=0 --- GRADE=05 RH=90 PROCESS=ADSORB DUST=0

OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
1	0.00	2.5000	2.5000	2.5000	1	0.00	2.6000	2.6000	2.6000
2	0.25	13.5700	13.5539	13.2967	2	0.25	15.4592	14.9557	15.4592
3	0.50	21.2233	20.1193	20.4033	3	0.50	22.4360	21.8503	22.6412
4	0.75	25.5967	24.8758	25.8017	4	0.75	27.5660	27.2431	27.9764
5	1.00	28.9450	29.0294	29.4917	5	1.00	31.1228	31.1341	30.5072
6	1.50	32.0200	32.1781	32.3617	6	1.50	35.2268	34.0012	33.8588
7	2.00	32.9767	33.4510	33.1133	7	2.00	37.3472	35.2982	35.3636
8	2.50	.	33.9199	.	8	2.50	.	36.0491	.
9	3.00	33.0450	35.6618	33.2500	9	3.00	38.1680	36.6635	37.8944
10	12.00	.	35.9967	.	10	4.00	38.6468	.	.
11	20.00	33.2500	.	33.5233	11	12.00	.	37.0731	.
					12	20.00	39.1940	.	.

GRADE=05 RH=75 PROCESS=ADSORB DUST=2 --- GRADE=05 RH=90 PROCESS=ADSORB DUST=2

OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
12	0.00	2.5000	2.5000	2.5000	13	0.00	2.6000	2.6000	2.6000
13	0.25	9.9363	11.7250	11.0752	14	0.25	13.9255	13.1884	11.9882
14	0.50	15.8317	17.8750	16.6356	15	0.50	20.6270	19.4878	17.7553
15	0.75	19.6503	22.1117	21.5261	16	0.75	25.9882	24.3129	22.7176
16	1.00	23.9379	26.4167	25.1706	17	1.00	29.4730	28.0657	26.4729
17	1.50	30.1683	29.3550	29.6324	18	1.50	33.3599	32.3547	32.1059
18	2.00	32.7810	32.7033	32.8480	19	2.00	35.4374	33.9630	34.7882
19	3.00	34.5229	36.5573	33.9869	20	2.50	.	34.9012	.
20	6.00	.	36.9400	36.0637	21	3.00	36.7106	35.9065	35.4588
21	10.00	35.9967	.	.	22	10.00	.	.	36.8671
22	12.00	.	37.0767	36.1977	23	20.00	38.0509	37.1798	.

GRADE=05 RH=75 PROCESS=ADSORB DUST=5 --- GRADE=05 RH=90 PROCESS=ADSORB DUST=5

OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
23	0.00	2.5000	2.5000	2.5000	24	0.00	2.6000	2.6000	2.6000
24	0.25	9.7238	11.8714	11.7413	25	0.25	11.5246	11.6069	11.6069
25	0.50	14.4746	17.4032	17.4683	26	0.50	17.8434	16.3714	16.4366
26	0.75	18.9651	21.5683	21.8937	27	0.75	23.1851	20.5485	20.6790
27	1.00	22.6746	24.9524	25.3429	28	1.00	26.7029	24.0076	24.3340
28	1.50	26.7746	29.5730	28.7270	29	1.50	31.1326	29.2290	29.8164
29	2.00	29.1175	31.1544	31.0048	30	2.00	33.4777	31.5134	31.9050
30	2.50	.	31.9810	31.9810	31	3.00	35.5623	34.7767	35.3641
31	3.00	33.4127	33.4778	32.5016	32	6.00	.	.	35.6905
32	10.00	34.7794	35.3000	.	33	10.00	36.9954	36.0821	.
33	12.00	.	.	35.4302					

*Three replications, A, B, C, of moisture content M against time, θ (theta), are shown here. Other relevant data are shown in Table IX.

TABLE XX

DYNAMIC SORPTION DATA FOR GRADE 12 SILICA GEL*

- GRADE=12 RH=20 PROCESS=DESORB DUST=0 ---					GRADE=12 RH=60 PROCESS=ADSORB DUST=0 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
1	0.0	36.00	36.00	36.00	1	0.0	2.50	10.30	10.30
2	0.5	33.90	34.08	33.92	2	0.5	4.90	12.68	12.70
3	1.0	32.02	32.00	31.97	3	1.0	7.12	13.66	13.72
4	2.0	28.62	28.56	28.59	4	2.0	11.11	16.43	16.58
5	3.0	25.70	25.69	25.79	5	3.0	14.31	18.88	19.02
6	4.0	23.41	23.27	23.33	6	4.0	17.06	20.91	21.12
7	6.0	19.54	19.67	19.53	7	6.0	21.53	24.20	24.34
8	8.0	16.88	16.71	16.83	8	8.0	24.37	26.49	26.58
9	16.0	12.00	12.10	11.98	9	12.0	28.31	29.15	29.25
10	24.0	13.71	10.70	10.26	10	16.0	30.11	30.63	30.58
					11	24.0	31.54	31.68	31.65

- GRADE=12 RH=20 PROCESS=DESORB DUST=2 ---					GRADE=12 RH=60 PROCESS=ADSORB DUST=2 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
11	0.0	36.00	36.00	36.00	12	0.0	2.50	2.50	2.50
12	0.5	34.37	34.39	34.38	13	0.5	4.36	4.35	4.36
13	1.0	32.91	32.87	32.88	14	1.0	6.11	6.02	6.01
14	2.0	30.12	30.15	30.16	15	2.0	9.22	9.31	9.24
15	3.0	27.68	27.81	27.72	16	3.0	12.00	12.13	12.01
16	4.0	25.60	25.49	25.57	17	4.0	14.43	14.39	14.51
17	6.0	22.08	22.18	22.13	18	6.0	18.43	18.54	18.49
18	8.0	19.35	19.46	19.39	19	8.0	21.56	21.51	21.61
19	16.0	13.59	13.50	13.55	20	12.0	25.80	25.83	25.75
20	24.0	11.45	11.48	11.49	21	16.0	28.29	28.27	28.32
					22	24.0	30.70	30.68	30.73

- GRADE=12 RH=20 PROCESS=DESORB DUST=5 ---					GRADE=12 RH=60 PROCESS=ADSORB DUST=5 -				
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
21	0.0	36.00	36.00	36.00	23	0.0	2.50	2.50	2.50
22	0.5	34.70	34.77	34.73	24	0.5	3.92	3.92	3.95
23	1.0	33.50	33.62	33.53	25	1.0	5.36	5.32	5.29
24	2.0	31.48	31.30	31.41	26	2.0	7.86	7.82	7.80
25	3.0	29.47	29.31	29.42	27	3.0	10.15	10.15	10.11
26	4.0	27.49	27.58	27.50	28	4.0	12.20	12.32	12.05
27	6.0	24.46	23.97	24.45	29	6.0	15.83	15.72	15.91
28	8.0	21.83	21.88	21.80	30	8.0	18.67	18.72	18.93
29	16.0	15.39	15.51	15.50	31	12.0	23.92	23.12	23.88
30	24.0	15.60	15.55	12.64	32	16.0	26.01	26.83	26.14
					33	24.0	29.53	29.13	29.29

TABLE XX (Continued)

GRADE=12	RH=75	PROCESS=ADSORB		DUST=0	GRADE=12	RH=90	PROCESS=ADSORB		DUST=0
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
1	0.0	2.50	10.50	10.50	1	0.0	2.50	10.50	10.50
2	0.5	5.34	13.01	12.54	2	0.5	5.40	12.34	13.02
3	1.0	7.83	14.49	15.17	3	1.0	8.06	14.51	14.92
4	2.0	12.42	18.28	17.72	4	2.0	12.58	18.08	19.01
5	3.0	16.11	20.58	21.16	5	3.0	16.73	21.04	22.14
6	4.0	18.94	23.09	23.64	6	4.0	20.25	23.98	25.63
7	6.0	24.01	26.71	26.99	7	6.0	25.07	28.11	28.14
8	8.0	27.53	29.45	29.83	8	8.0	28.52	31.26	31.03
9	12.0	31.72	32.75	32.82	9	12.0	34.29	33.31	34.61
10	16.0	33.83	34.56	34.62	10	16.0	35.71	36.12	36.48
11	24.0	35.55	35.71	35.81	11	24.0	37.25	37.42	37.68

GRADE=12	RH=75	PROCESS=ADSORB		DUST=2	GRADE=12	RH=90	PROCESS=ADSORB		DUST=2
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
12	0.0	2.50	2.50	2.50	12	0.0	2.50	2.50	2.50
13	0.5	4.43	4.50	4.67	13	0.5	4.65	5.11	4.96
14	1.0	6.43	6.71	6.63	14	1.0	7.12	6.91	6.64
15	2.0	10.07	11.01	10.10	15	2.0	10.45	11.33	10.48
16	3.0	13.05	13.83	13.31	16	3.0	13.43	14.52	13.73
17	4.0	16.00	16.62	16.15	17	4.0	16.58	17.34	16.87
18	6.0	20.06	21.08	20.57	18	6.0	22.31	21.98	21.52
19	8.0	24.06	24.69	24.21	19	8.0	26.01	25.61	25.21
20	12.0	29.42	29.62	29.37	20	12.0	30.64	30.31	30.03
21	16.0	31.92	31.84	31.81	21	16.0	33.30	33.91	33.27
22	24.0	34.40	35.01	34.32	22	24.0	36.04	36.48	36.37

GRADE=12	RH=75	PROCESS=ADSORB		DUST=5	GRADE=12	RH=90	PROCESS=ADSORB		DUST=5
OBS	THETA	M_A	M_B	M_C	OBS	THETA	M_A	M_B	M_C
23	0.0	2.50	2.50	2.50	23	0.0	2.50	2.50	2.50
24	0.5	4.12	4.28	4.19	24	0.5	4.21	4.35	4.30
25	1.0	5.71	5.61	5.74	25	1.0	5.89	5.71	5.69
26	2.0	8.49	8.63	8.57	26	2.0	8.72	9.01	8.83
27	3.0	11.15	11.56	11.32	27	3.0	11.70	11.56	11.62
28	4.0	13.43	13.61	13.57	28	4.0	14.29	13.81	15.00
29	6.0	17.59	17.75	17.58	29	6.0	17.65	19.03	18.56
30	8.0	20.99	21.25	20.98	30	8.0	21.67	22.54	22.07
31	12.0	25.95	26.28	26.02	31	12.0	27.19	28.00	27.18
32	16.0	29.28	29.42	29.32	32	16.0	30.70	31.02	30.69
33	24.0	33.05	33.17	33.11	33	24.0	34.61	34.81	34.53

*Three replications, A, B, C, of moisture content M against time, θ (theta), are shown here. Other relevant data are shown in Table X.

VITA

Shah Muhammad Farouk

Candidate for the Degree of

Doctor of Philosophy

Thesis: THE EFFECTS OF DUST CONTAMINATION ON THE SORPTION CHARACTERIS-
TICS OF SILICA GEL

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Mymensingh, Bangladesh, August 19, 1941,
the son of Mr. and Mrs. Shah Wajed Ali; married to Raihana
Ahmed in 1974; son, Fahmid, born on November 25, 1975.

Education: Matriculated from Mymensingh Zilla School, Mymensingh,
Bangladesh, and completed higher secondary education from
Ananda Mohan College, Mymensingh, Bangladesh, in 1959;
received the degree of Bachelor of Science in Mechanical
Engineering from the Bangladesh University of Engineering and
Technology, Dacca, Bangladesh, in 1963; received degree of
Master of Science in Agricultural Engineering from the Texas
A & M University in August, 1967; completed the requirements
for the Doctor of Philosophy degree at Oklahoma State
University in May, 1979.

Professional Experience: Assistant Engineer with the Power Wing
of the Water and Power Development Authority of Bangladesh
(formerly East Pakistan), 1963-1965; Trainee in Agricultural
Engineering, Bangladesh Agricultural University, 1965-1967;
Member of the Faculty of Agricultural Engineering, Bangladesh
Agricultural University, Mymensingh, Bangladesh, 1967-1975;
Graduate Research Assistant in the Agricultural Engineering
Department, Oklahoma State University, 1976-1979.

Professional Organizations: Associate Member of the Bangladesh
Institute of Engineers; Associate Member of the American
Society of Agricultural Engineers up to 1976.