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BACTERIAL ADSORPTION ON SOILS—THERMODYNAMICS

by

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This report is submitted in partial fulfillment of Grant No. 16060 EBD between the Federal Water Pollution Control Administration and Utah Water Research Laboratory in cooperation with the College of Science both at Utah State University

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ABSTRACT

Laboratory studies on the adsorption of bacteria onto soils and activated carbon were undertaken to evaluate the role of the process in removal of bacteria from groundwater. It was hypothesized that removal of bacteria from water passing through soil would be primarily due to adsorption in which case the bacteria would behave in a manner similar to colloidal particles or chemical molecules.

The basic kinetics of uptake of *Staphylococcus aureus* were determined on activated carbon, a highly adsorbing material chemically speaking. Once the technique was worked out and adsorption demonstrated to take place, sand, clay, and Mendon silt loam were studied. Uptake of bacteria was observed microscopically on both activated carbon and clay. Sand showed no measurable uptake of bacteria.

Mendon silt loam was also used in competitive adsorption studies. Sodium chloride, sodium lauryl sulfate and peptone were used and their effects on adsorption of the test organism measured.

Results clearly showed uptake of the bacteria with equilibrium reached within one hour. Conventional chemical thermodynamics can be applied to bacterial adsorption onto soils with the determination of Langmuir type isotherms and the subsequent evaluation of ΔF°, ΔH°, and ΔS° functions. Bacterial adsorption is endothermic with peptone decreasing and sodium chloride increasing adsorption.

Based on the results, columns of sand and charcoal were set up and the time of bacterial passage predicted by a first generation model. The results indicated reasonable fit for the model but some adjustment would be required for a close simulation.

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Key Words: Bacterial adsorption, soil, thermodynamics of bacterial adsorption competitive adsorption, activated charcoal, sand, clay, Mendon silt loam, *Staphylococcus aureus.*

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INTRODUCTION

The propensity of microorganisms to travel through soils saturated with moisture is a question ascertained largely by field observations and empirical experiments. The aggregate mass of field observations (AWWA, 1960; Woodward, 1961) indicates that bacteria will travel far, in terms of miles, through fissured rock or gravel, but only short distances, in terms of tens of feet, through finer textured media such as sand. In a rather definitive experiment, which consisted of injected raw sewage in an injection well, Krone et al., (1958) reports 100 feet was the nominal limit of travel distance of bacteria. Laboratory studies feeding soil columns with sewage water (Robeck et al., 1962) have shown that bacteria will eventually break through after weeks of feeding; the rise in bacterial count was exponential when it did occur. Filmer and Corey (1966), Cookson and North (1967), Drewry and Eliassen (1968), and Cookson (1969) have shown viruses to be adsorbed by soil particles. Filmer and Corey (1966) have demonstrated that bacterial size particles are removed by soil; Boyd et al. (1969) have demonstrated bacterial removal by soils. Thus it is clear that some mechanism acts to inhibit the free travel of bacteria through saturated soils. Adsorption by soil particles, mechanical sieving, and microsedimentation are possible mechanisms (O'Melia and Stumm, 1967; Cookson, 1970) causing bacterial retention; population change is another consideration. We focus herein on the adsorption process (Hendricks et al., 1969).

Objectives

Our primary goal was to describe and explain bacterial adsorption on soils in terms of thermodynamics. By corollary, we also sought to ascertain the influence of temperature, chemical competition, and soil type on the process of bacterial adsorption.

Significance

Untreated waste waters often find their way inadvertently into bodies of groundwater—one of the largest and most extensive sources of water supply in the United States. Septic tank tile fields constitute probably the most extensive source of such waste waters, and are a hazard to wells located nearby. Two well known cases of direct recycle from septic tank to well are Suffolk Co. Long Island (Flynn, 1961) and Twin Cities area of Minnesota (Woodward, 1961).

Treated waste waters are now being injected directly into aquifers (Parkhurst, 1965). This form of recycle is discussed with increasing frequency. The question of travel of residual microorganisms is often noted as an unknown parameter, which needs to be determined prior to large scale injection of treated waste waters into groundwaters.

Empiricism is invaluable in providing guidance in assessing such situations. However, microorganism retention in soils needs to be evaluated also in terms of a theoretical framework if such practical questions are to be dealt with comprehensively. Our project relates to developing means for rational assessment of bacterial travel through saturated soils. Some practical situations for application include artificial recharge with waste waters, septic tank hazards, and shallow aquifer contamination.

THEORY OF BACTERIAL ADSORPTION

Adsorption

A *process* is a transition between states; a chemical *reaction* is a type of process. Adsorption is a type of reaction, or process, involving an *adsorbate* in a relatively mobile or free state which becomes bonded to a site on an *adsorbent* surface. Adsorption generally involves the same type of bonding that occurs in normal chemical reactions; however, for conceptual purposes bonding can be categorized as:

(1) electrostatic attraction between unlike charges; simple ion exchange is an example
(2) van der Waal's attraction caused by non-homogeneous force fields; the Leonard-Jones 6-12 potential describes this mathematically
(3) valence bonds; this is the usual bonding for chemical reactions

Forces involved in adsorption are similar to those that occur in common chemical reactions, except that one of the interacting molecules, atoms, or ions is a constituent of a surface. Thus the resultant force of reaction between adsorbent and adsorbate is modified (increased or decreased) by the presence of neighboring constituents which make up the solid surface. The bonding categories above are somewhat arbitrary in that they are all part of a continuum.

Bacteria and thermodynamics

Thermodynamics can be applied to the adsorption process to derive useful information and insight regarding equilibria, bonding energy, and entropy changes. Classical thermodynamics tell much of practical usefulness, whereas application of statistical thermodynamics can yield greater fundamental understanding. We apply these concepts here to the bacterial adsorption reaction, hypothesizing that this process can be treated as any normal chemical reaction. Certainly this view is consistent and logical since the bacterium does change state (from free to adsorbed state) during the adsorption reaction. Bacterial adsorption differs, however, from the usual chemical reaction or phase change in the nature of the adsorbate species undergoing a change in state. Bacteria are macroparticles whereas the usual application of thermodynamics concerns state changes at the molecular level. The essential practical difference between the two cases is that the magnitudes of the thermodynamic functions obtained for bacterial adsorption may not be directly comparable with thermodynamic data for the adsorption of molecules. It is our contention that the meaning and interpretation of the data should not be affected except insofar as experience with the adsorbate species limits the interpretation of data.

Adsorption reaction. Thermodynamics can be used to describe the change of *state* of a substance or the energy change involved in a given reaction or process. Thus the initial and final states of the reactants and products must be clearly identified, which in biological systems is sometimes hazardous.

For the bacterial adsorption reaction, the simplest equation which can be written is:

$$\text{Bacteria} + \text{Sorbent} \rightleftarrows \text{Bacteria}\cdot\text{Sorbent} \quad \ldots \quad (1)$$

Designating bacteria as B, X as the sorbent, and $\overline{X}$ as the bacteria sorbent complex, Equation (1) is rewritten:

$$B + X \rightleftarrows \overline{X} \quad \ldots\ldots\ldots \quad (2)$$

The above is an obvious oversimplification of the bacteria-sorbent reaction since it ignores the critical role of the solvent in its representation. It is commonly accepted that both bacteria and soil particles are strongly hydrophilic. Thus it is possible to expand Equation (2) into component partial reactions as follows:

$$B\cdot W_y \rightleftarrows B + yW \qquad \Delta H_{BW} \quad \ldots\ldots \quad (3)$$

$$X\cdot W_z \rightleftarrows X + zW \qquad \Delta H_{XW} \quad \ldots\ldots \quad (4)$$

$$B + X \rightleftarrows B\cdot X \qquad \Delta H_{BX} \quad \ldots\ldots \quad (5)$$

in which y and z represent the number of molecules of water, W, associated with the bacteria and the adsorbent site, respectively. When (3), (4), and (5) are added:

$$B \cdot W_y + X\,W_z \rightleftharpoons B \cdot X + (y+z)W \quad \Delta H_{BXW} \quad . \quad (6)$$

The measurement of ΔH_{BXW} gives a value of the heat (enthalpy) of the adsorption process of bacteria from aqueous solution. Since the bacteria-soil reaction occurs in the presence of soil moisture, Equation (6) gives a more complete picture of the adsorption process which occurs in natural systems and forms the model by which experimental data are explained. Although Equation (6) indicates the bacteria-sorbent complex is completely dehydrated, this situation is highly unlikely. It is reasonable to assume that the surface complex is still hydrated although to a lesser degree than the reactants prior to interaction. If one is interested only in the affinity of the bacteria for the solid, the reaction involving ΔH_{BX} must be isolated, i.e., the energy of desorption of water must be eliminated from the process. Further, it must be assumed that the solid is inert and only serves as the source of a force field and the energy change represented by ΔH_{BX} is attributed only to the soil-bacterium couple. An attempt to isolate ΔH_{BX} would require

(a) Data concerning the ΔH of desorption of water from the solid.
(b) Data concerning the ΔH of desorption of water from the bacterium.
(c) Knowledge of the amount of water desorbed from the solid and bacterium during the formation of the bacteria-soil complex.

Because of the lack of pertinent data, any attempt to calculate a value for ΔH_{BX} must be regarded only as a mathematical exercise. However, since Equation (6) is regarded as the natural system, i.e., bacteria are usually adsorbed from the aqueous phase, Equation (6) is of greatest importance. Equations (3), (4), and (5) are written to clarify and explain Equation (6).

Equilibrium. The mathematical statement for equilibrium involving Equation (6) is:

$$\alpha = \frac{[B \cdot X]^*}{[B \cdot W_y]^* [X \cdot W_z]^*} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$= \frac{\bar{X}^*}{C^* X^*} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

in which

α = reaction equilibrium constant (ml/sites available)
$\bar{X}^*$ = equilibrium concentration of cells adsorbed per gram of soil
C^* = equilibrium solution concentration of hydrated bacteria (cells/ml)
X^* = equilibrium concentration of hydrated adsorption sites unoccupied by bacteria (sites/gm)

Because of the excess of water, the term $(y+z)W$ is assumed constant and incorporated in the value of α. Now we let

$$X^* = X_m - \bar{X}^* \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

in which

X_m = maximum number of sorption sites per gram of soil

and substitute (9) in (8) to give:

$$\alpha = \frac{\bar{X}^*}{(X_m - \bar{X}^*)\, C^*} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Algebraically rearranging (10) gives:

$$\frac{\bar{X}^*}{X_m} = \frac{\alpha C^*}{1 + \alpha C^*} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

—which is the usual algebraic arrangement for the well known Langmuir isotherm.

The linearized form of the Langmuir isotherm is obtained by algebraic rearrangement of Equation (11), which gives:

$$\frac{C^*}{\bar{X}^*} = \frac{1}{X_m} C^* + \frac{1}{\alpha X_m} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

This form of the equation is useful, as will be seen later, in analysis of data.

Thermodynamics. Measurement of the equilibrium or Langmuir constant, α, and how it varies with temperature is the general procedure of obtaining critical thermodynamic data. The equilibrium constant, α, is related to standard free energy, ΔF°, by the equation (Equation A-29, Appendix A):

$$\Delta F^\circ = - RT \ln \alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Differentiating with respect to temperature

$$- \frac{d(\Delta F^\circ)}{dT} = R \ln \alpha + RT \frac{d \ln \alpha}{dT} \quad . \quad . \quad . \quad (14)$$

When the reactants and products are in their standard state, the Gibb's-Helmholtz equation is (Equation A-35, Appendix A):

$$\Delta F^{o} - \Delta H^{o} = T \frac{d(\Delta F^{o})}{dT} \quad \ldots . (15)$$

Substituting Equation (15) in Equation (14) the following results:

$$- \Delta F^{o} + \Delta H^{o} = RT \ln \alpha + RT^{2} \frac{d \ln \alpha}{dT} \quad \ldots . (16)$$

After substituting $\Delta F^{o} = - RT \ln \alpha$ in Equation (16) and rearranging, the following relation can be obtained:

$$\frac{d \ln \alpha}{dT} = - \frac{\Delta H^{o}}{RT^{2}} \quad \ldots . (17)$$

Integrating Equation (17) and assuming ΔH^{o} constant over the temperature range of the study, the following is derived:

$$\ln \alpha = - \frac{\Delta H^{o}}{RT} + C \quad \ldots . (18)$$

in which

- C = integration constant
- ΔH^{o} = standard state enthalpy of reaction
- R = gas constant
- T = absolute temperature (°K)

That $C = \Delta S^{o}/R$ (Equation 18) can be shown as follows: The Gibb's free energy ΔF^{o} is defined as

$$\Delta F^{o} = \Delta H^{o} - T \Delta S^{o} \quad \ldots . (19)$$

or as

$$\Delta F^{o} = - RT \ln \alpha \quad \ldots . (13)$$

Substituting $\Delta H^{o} - T \Delta S^{o}$ for ΔF^{o}, and rearranging, Equation (13) becomes

$$\ln \alpha = - \frac{\Delta H^{o}}{RT} + \frac{\Delta S^{o}}{R} \quad \ldots . (20)$$

Thus by measurement of α and its corresponding temperature dependence, the thermodynamic functions, ΔF^{o}, ΔH^{o}, and ΔS^{o}, for a given process can be evaluated by Equations (13) and (20) respectively. These functions provide valuable information concerning the reaction in question. The model of the reaction can be more accurately inferred through deductive reasoning consistent with the experimentally derived thermodynamic values.

Equation A-25, Appendix A, reproduced below as Equation (21),

$$\Delta F = \Delta F^{o} + RT \ln Q \quad \ldots . (21)$$

offers the means for assessing the direction of equilibrium and the degree of deviation from it. Since ΔF^{o} is a constant determined for any given temperature, we need only specify the value of Q, which is the ratio of concentrations of products to reactants, each substance raised to its stoichiometric power.

While we are applying thermodynamics to reactions involving bacteria—which are finite particles—conventional thermodynamics was developed for particles at the molecular level. We hypothesize that the colligative properties of molecules can be extended to apply to bacterial particles. This can be done by use of the activity concept. Thus "bacterial activity" relates molecular behavior, which conforms to the ideal gas law, to bacterial concentration. We allow for use of molar concentration expressions by the activity coefficient, γ thus

$$a_{B} = \gamma_{B} \cdot [B] \quad \ldots . (22)$$

in which

- a_{B} = bacterial activity
- γ_{B} = bacterial activity coefficient
- [B] = bacterial concentration (moles/liter)

It is implied that a "mole of bacteria" is Avogadro's number, 6.02×10^{23}. We use the osmotic pressure to relate the colligative properties of bacterial particle thermodynamics to those of molecular particle thermodynamic, letting γ_{B} be the calculated unknown. Thus from van't Hoff's law:

$$\pi = \gamma_{B} [B] RT \quad \ldots . (23)$$

in which

- π = measured osmotic pressure (atmospheres)

Competitive adsorption

Competitive adsorption is defined as the competition for adsorption sites by two or more adsorbate species

(excluding the solvent). This case is analyzed by the expansion of the reaction equations to include additional adsorbate species. Let us designate A as a chemical species which competes with bacteria for the soil sorption sites. The two important reactions involving A are its (1) direct competition with bacteria for the surface sites forming the surface complex A•X and (2) the interaction of the chemical species with the bacteria forming a chemical-bacteria complex, A•B. These reactions are shown below

$$A \cdot W_v + X \cdot W_2 \rightleftarrows A \cdot X + (v+z)W \quad \Delta H_{AX} = \quad \ldots\ldots\ldots\ldots (24)$$

$$A \cdot W_v + B \cdot W_y \rightleftarrows A \cdot B + (v+y)W \quad \Delta H_{AB} = \quad \ldots\ldots\ldots\ldots (25)$$

in which v designates the number of water molecules W associated with the chemical species A. Combining Equations (24) and (25) we have:

$$2\ A \cdot W_v + X \cdot W_z + B \cdot W_y \rightleftarrows A \cdot X + A \cdot B + (2v+y)W \quad \ldots\ldots\ldots\ldots (26)$$

Combining Equation (26) with Equation (6) we obtain the net reaction:

$$2A \cdot W_v + 2X \cdot W_z + 2B \cdot W_y \rightleftarrows A \cdot X + A \cdot B + B \cdot X + 2(v+y+z)W \quad \ldots\ldots\ldots\ldots (27)$$

If we assume negligible interaction between the bacteria and A, Equation (27) can be reduced to:

$$A \cdot W_v + X \cdot W_z + B \cdot W_y \rightleftarrows aA \cdot X + bB \cdot X + (v+y+z)W \quad \ldots\ldots\ldots\ldots (28)$$

in which

$$a + b = 1$$

Equilibrium for Equation (28) is expressed:

$$\alpha' = \frac{[B \cdot X]^* [A \cdot X]^*}{[X \cdot W]^* [B \cdot W]^* [A \cdot W]^*} \quad \ldots (29)$$

Because of the large excess of water in the system the solvent concentration is assumed constant and its value is incorporated in the value of α'. An equivalent form of Equation (29) is:

$$\alpha' = \frac{\overline{X}^* \cdot \overline{X}_A^*}{X^* \cdot C^* \cdot A^*} \quad \ldots\ldots (30)$$

in which

α' = equilibrium constant for Equation (28)

$\overline{X}_A^*$ = $[A \cdot X]^*$, the equilibrium concentration of A adsorbed (gm chemical sorbate/gm sorbent)

A^* = $[A \cdot W]^*$, equilibrium concentration of A in the liquid phase (gm/L)

Equation (29) can be rewritten by substituting

$$X^* = X_m - \overline{X}^* - \overline{X}_A^* \quad \ldots\ldots (31)$$

as follows:

$$\alpha' = \frac{\overline{X}^* \cdot \overline{X}_A^*}{(X_m - \overline{X}^* - \overline{X}_A^*) \cdot C^* \cdot A^*} \quad \ldots (32)$$

Rearranging Equation (32) gives the equivalent Langmuir isotherm expression for two sorbates:

$$\frac{\overline{X}^*}{X_m} = \frac{(X_m - \overline{X}_A^*)}{X_m} \frac{\alpha' C^* A^*}{(\overline{X}_A^* + \alpha' C^* A^*)} \quad \ldots (33)$$

If A^* and $\overline{X}_A^*$ are held constant while changing C^*, the shape of the equilibrium graph for the fractional coverage by bacteria will resemble the plot of the Langmuir isotherm. However, the asymptote of the bacterial isotherm will drop proportionately with sites occupied by A; and α' will probably be unique for every level of A^*.

The linearized form of Equation (33) is:

$$\frac{C^*}{\overline{X}^*} = \frac{1}{(X_m - \overline{X}_A^*)} C^* + \frac{\overline{X}_A^*}{\alpha' A^* (X_m - \overline{X}_A^*)} \quad (34)$$

which is presented merely to show the contrast with another form below.

Laidler (1965, p. 262) presents an alternate expression for two sorbates (bacteria and chemical in this case) competing for adsorption sites as:

$$\frac{\overrightarrow{X}^*}{X_m} = \frac{\alpha C^*}{1 + \alpha C^* + \alpha' A^*} \quad . \quad . \quad . \quad (35)$$

The linearized form of Equation (35) is

$$\frac{C^*}{\overrightarrow{X}^*} = \frac{1}{X_m} C^* + \left[\frac{1}{\alpha X_m} + \frac{\alpha' A^*}{\alpha X_m}\right] \quad . \quad . \quad (36)$$

We use Equations (35) and (36) in further discussion since Equation (35) is found in the literature and appears rational.

Now if we further examine the differences between Equations (12) and (36) for cases of no competition and adding A as a competitor, respectively, we see the only difference lies in the intercept terms. It is Equation (12) that is used later, even when competitive effects are examined, so now we wish to ascertain the effect of using the wrong equation when competition is involved. We do this by equating the intercept portions of Equations (12) and (36). First, however, to distinguish α's let us designate with subscripts T for *true* for Equation (36) and P for *psuedo* for Equation (12). Thus we have:

$$\alpha_T = \alpha_P (1 + \alpha' A^*) \quad . \quad . \quad . \quad . \quad . \quad (37)$$

Thus α_P is the lower limit of α_T, and

$$\alpha_T \rightarrow \alpha_P \quad \text{as} \quad \alpha' A^* \rightarrow 0.$$

In interpreting results later, we use α_p; we make no further reference to these differences except to point out that such differences do exist and they are mathematically delineated in the foregoing. To do more would be arduous and involved, with few quantitative returns.

Thermodynamics. The thermodynamics of competitive adsorption differs from the case of singular sorbate adsorption only insofar as more terms are involved in the reaction (Equations 25 - 28). The reaction thermodynamics for Equation (28), determined from equilibrium data as given by Equations (13) and (20), will probably result in values different from those obtained using Equation (6). This reflects two simultaneous reactions occurring on the interface resulting in an energy balance which is the net contribution of each individual reaction. For example if

$$\Delta H_{AX} >> \Delta H_{BX}$$

then we may expect for the stoichiometry coefficients,

$$a >> b$$

Statistical thermodynamics

Another way to examine the thermodynamics of adsorption is at the particle level. This is useful in providing a more rigorous definition and understanding concerning fundamental mechanisms of adsorption; empirical coefficients then have greater significance. Statistical thermodynamics is based upon models of particle behavior; we will carry this no farther than the particle model.

Hill (1960) gives the molecular expression of $\alpha(T)$ as:

$$\alpha(T) = q(T) \cdot e^{\mu_o(T)/kT} \quad . \quad . \quad . \quad . \quad (38)$$

in which

$$q(T) = (q_x q_y q_z) \cdot e^{-U_{oo}/kT} \quad . \quad . \quad . \quad (39)$$

in which

$\alpha(T)$	=	α, the Langmuir isotherm equilibrium constant
$q(T)$	=	an harmonic oscillator molecular partition function
$\mu_o(T)$	=	chemical potential at an arbitrary standard state
k	=	Boltzman constant
U_{oo}	=	potential energy at the minimum in the potential well engulfing the adsorption site
q_x, q_y, q_z	=	one-dimensional harmonic-oscillator molecular partition functions, respectively

The terms q_x, q_y, q_z are for a monatomic molecule in a gas environment vibrating about an adsorption site, with x, y, and z components of motion. Statistical thermodynamic models have been developed successfully only for models of the gaseous state. Such models are not determinate for liquids, and application to macroparticles has not been attempted. The indeterminacy of the adsorbed bacterium model still does not obviate the usefulness and insight which is possible by empirically applying the statistical thermodynamic concepts express-

ed in Equations (38) and (39). We do this merely by postulating that the adsorbed bacterium must have some particle partition function, q(T), associated with it. This partition function reflects all of the properties of the partition function which includes the types of motion or energy states accessible to the adsorbed bacterium.

The relationship between the classical and statistical thermodynamic functions can be seen by equating Equation (20) and Equation (38). Thus:

$$-\frac{\Delta H^{o}}{RT} = \frac{\mu_{o}(T)}{kT} \quad \cdots\cdots\cdots (40)$$

and

$$\frac{\Delta S^{o}}{R} = \ln q(T) \quad \cdots\cdots\cdots (41)$$

in which ΔH^{o} and ΔS^{o} are for the partial reaction of Equation (5) and therefore these terms are ΔH^{o}_{BX} and ΔS^{o}_{BX}, respectively. Equation (41) is not strictly correct, however, as the left side refers to a mole of particles and the right side refers to a single particle; this is true for Equation (40) also but the equality holds. For the entropy function, the number of particles involved does make a difference as the number of ways M adsorption sites can be occupied by N particles affects the entropy term also. The ΔS^{o} term refers to a mole of particles and not a single particle, thus it is not compatible with q(T), which is the number of energy states accessible to a single particle. We call this partition function for the ensemble of particles, Q(T); Equation (41) must be modified to give:

$$\frac{\Delta S^{o}}{R} = \ln Q(T) \quad \cdots\cdots\cdots (42)$$

Since a solution environment is involved, we say Q(T) is the change in accessible quantum states in going from the solution environment to an adsorbed condition. The same is true for $\mu_{o}(T)$. This contrasts with the usual statistical thermodynamic treatment, which is developed for gas adsorption (Hill, 1960).

If we could isolate ΔH_{BX} and ΔS_{BX} we could speculate quantitatively on the nature of the bond and on the bacterial entropy changes. We must remain qualitative for the present, however, which still allows us to glean insight and rationale concerning the reaction.

MATERIALS AND METHODS

The uptake of bacteria from the suspended phase to the adsorbed phase was determined by measuring the depletion of bacteria from the solution. This was done by providing opportunity for contact between the bacteria and adsorbent particles through mixing. The bacterial concentrations were measured at selected time intervals until the uptake on the particles was completed, which was assumed to be the equilibrium state. The number of bacteria depleted from suspension was assumed to be adsorbed by the soil sample; a control which contained a similar number of bacteria in distilled water was used to verify this assumption. Microscopic observation of attached cells also demonstrated bacterial uptake. At equilibrium the designations $\overline{X}^*$ and C^* were used to indicate the concentration of bacteria on solid phase (number of bacteria per gram of soil) and in the suspension phase (number of bacteria per ml of suspension), respectively. The values of $\overline{X}^*$ and C^* provided one point on an isotherm. All media and equipment were autoclaved at 121C. Aseptic technique was rigorously applied for all steps in the analysis.

Adsorbate—organism and preparation

The bacterium chosen for this study was *Staphylococcus aureus,* FDA 209, a spherical coccus that readily breaks up into individual cells upon shaking.

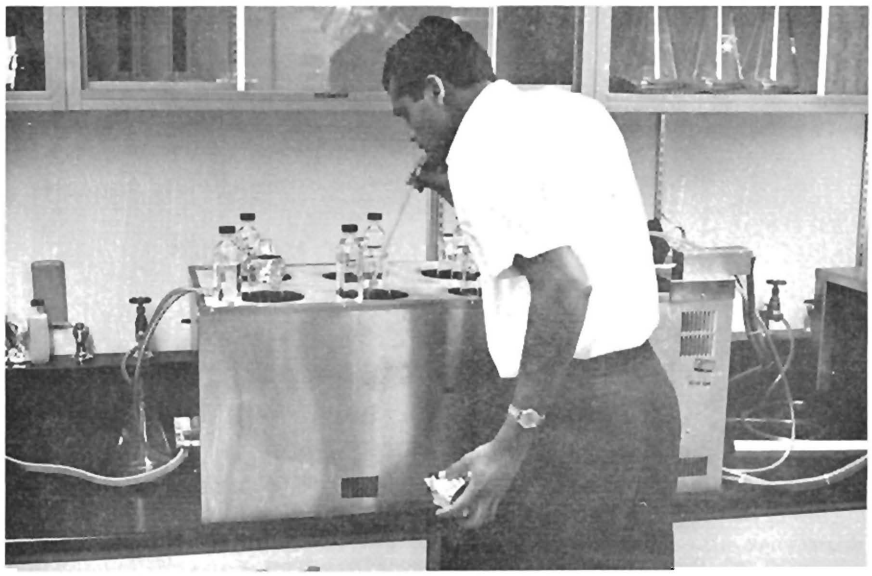
To maintain this organism, primary stock cultures were transferred at monthly intervals on Nutrient Agar (Difco) slants, and, after sufficient growth, were stored at 5C. Use stocks were made from the primary stocks as needed and transferred daily on Nutrient Agar slants. When an experiment was performed, the transfer for the next day's experiment was first made, then the slant (18 - 24 hours old) was used to prepare the suspension for the experiment. The slant was washed with 1 ml of sterile distilled water and the resulting suspension was then transferred drop by drop to sterile screw cap test tube containing 10 ml of sterile distilled water, until the optical density at 525 m_μ on a Spectronic-20 colorimeter was 0.3. The tube was then shaken vigorously for 15 minutes to suspend the cells and break up the clumps. An optical density of 0.3 for the organism described here corresponds to approximately 3×10^8 cells per ml and served as a means of calibration for obtaining the desired cell concentrations by adding a predetermined amount of a dilution to the reaction flasks. When large amounts of cells were required, the culture was grown on the surface of agar plates and harvested by flooding with 10 ml of sterile distilled water. The resultant suspension was then collected in a large sterile bottle. A sufficient amount of this suspension (determined as above) was added to the reaction flasks to provide the desired concentration of bacteria per ml in the flask. Each flask contained a magnetic stir-bar and a weighed amount of soil.

The assay

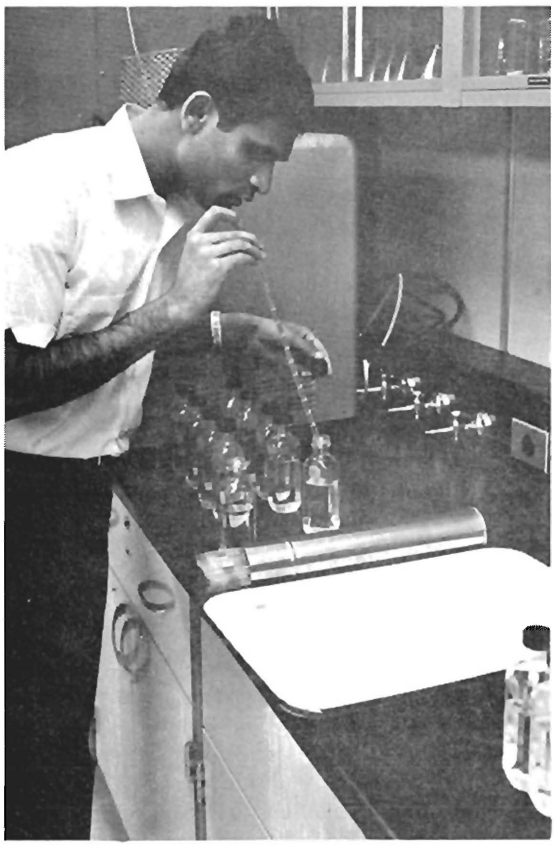
A 1 ml sample was removed from the flask supernatant after a brief period to allow the larger particles to settle out. Dilutions were made in accordance with the estimated initial concentration and 1 ml portions of several dilutions were passed through 0.45 μ membrane filters (Millipore Filter Corp.) so that at least one dilution would provide 30-300 cells on the filter. The filters were then placed in petri dishes on pads containing 2.2 ml of double strength Brain Heart Infusion Broth (Difco) and incubated at 37 C for 24 hours. Filters with 30-300 colonies were counted using a stereomicroscope at 30X. The control served as a base-line and provided the initial inoculum level at zero-time for all the flasks. Microscopic checks were made to determine if observed reduction in the presence of an adsorbent was due to clumping. No greater tendency to clump was observed in the presence of adsorbent than in the control.

The laboratory setup and the performance of the assay are illustrated in the series of photographs in Figure 1(a-g).

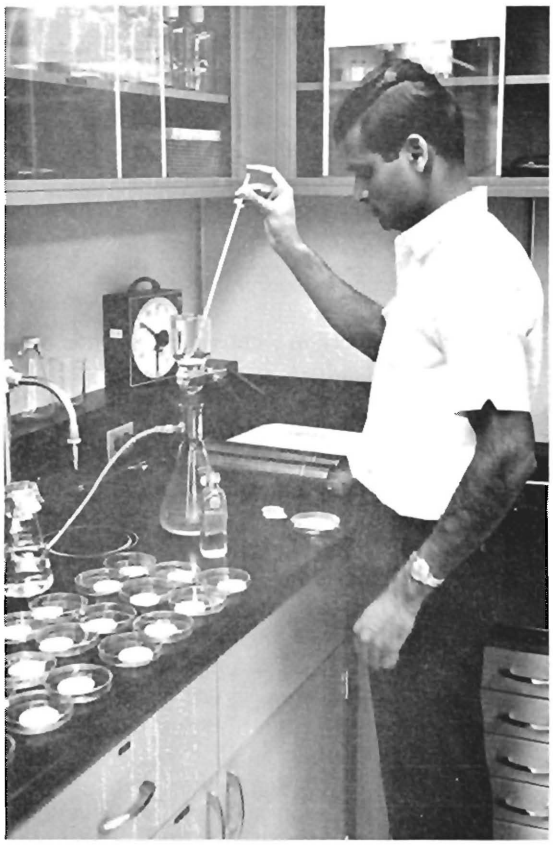
Coulter counter. A two month exploration was undertaken to ascertain the capability of the Model-B Coulter counter for counting bacteria—in lieu of the laborious plate counting technique. The results with the electronic counter did not agree with microscopic or plate counts. This was determined to be due in part to equipment problems. The orifice used for counting frequently clogged due to fairly large soil particles occasionally encountered. Use of this instrument was finally abandoned, in the interest of time, for the more reliable membrane counting procedure.



(a) Taking 1 ml sample from experimental flask

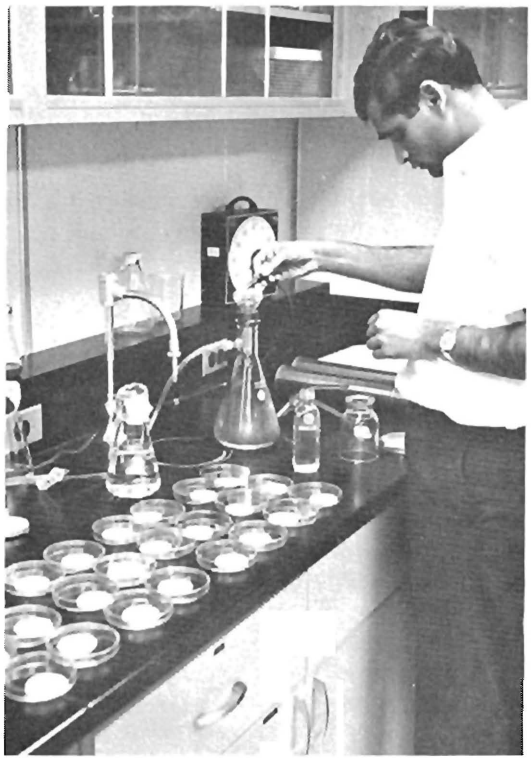


(b) Diluting the sample

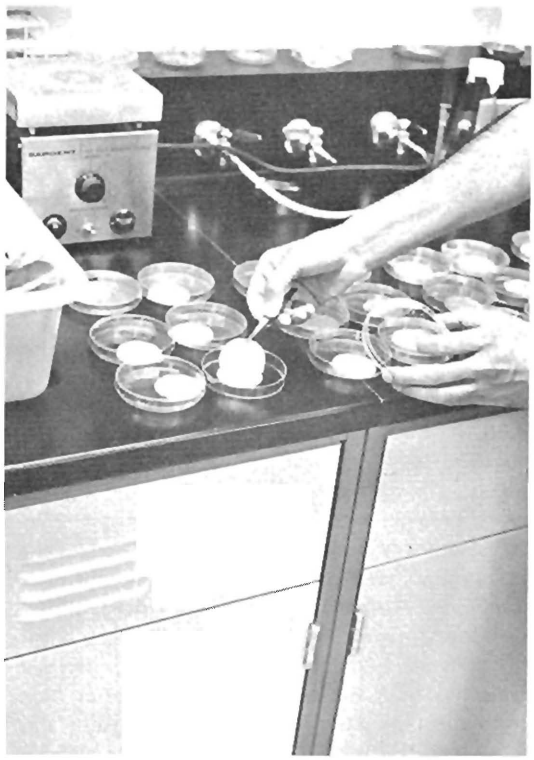


(c) Filtering the sample through .45 μ filter (Millipore)

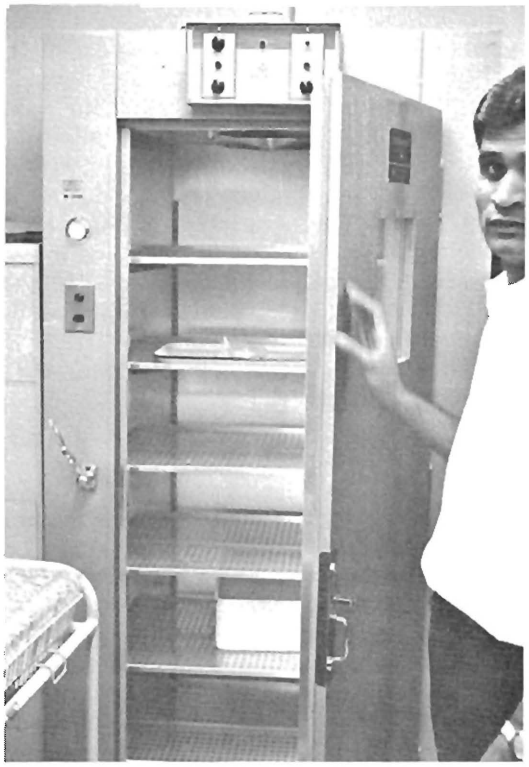
Figure 1. Photographs illustrating experimental procedure for counting bacteria.



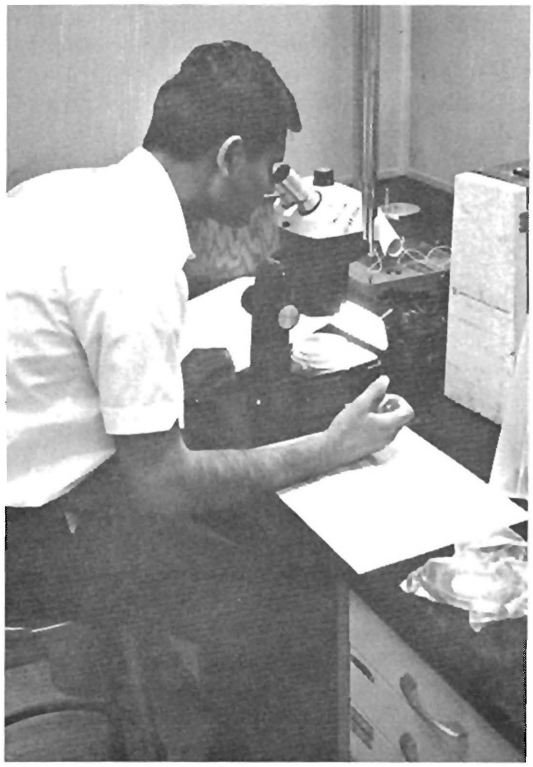
(d) Removing the filter paper aseptically from the filtering unit



(e) Placing the filter paper in petridish containing pads with 2.2 ml BHI.



(f) Incubating the samples at 37 C for 18 hours



(g) Counting the bacterial colonies by stereomicroscope at 30X and recording the counts on IBM coding sheet.

Figure 1. Continued.

Adsorbents

Activated charcoal. Activated charcoal (Filtrasorb 400, Calgon Co., Pittsburgh) was used to establish the operational procedures and to test the thermodynamic hypotheses of adsorption. Activated charcoal is desirable for this purpose since it: (1) is easy to handle, (2) will settle readily, (3) possesses large surface area, and (4) an abundant literature exists attesting to its adsorbent characteristics.

Since this assay procedure depends on viable cells, the question arose whether something in or on the charcoal might kill the cells which would also give a decrease in numbers. To test this possibility, ion permeable collodion bags were placed in the flasks containing charcoal and the system equilibrated for 24 hours. The bacterial suspension was then placed inside the collodion bag and samples removed periodically. No decline in bacterial numbers was observed suggesting that no toxic agent is released from the charcoal or if it is, it is a very large molecule (protein in size) which is unable to pass through the membrane. On the basis of this experiment, it was concluded that the reduction in bacterial numbers was due to the removal of cells from suspension and not due to bactericidal ions. The possibility of extraneous clumping was eliminated by microscopic examination.

Kaolinite clay. The first soil material used was Kaolinite clay. This clay is described as possessing: (1) 2 meq per 100 gm cation exchange capacity, (2) a pH of 4.4 when suspended in distilled water, (3) a surface area of 12 m^2 per gm, and (4) roughly hexagonal plate-like crystals 0.2 to 2 μ in size.

Mendon silt loam. An homogeneous portion of Mendon silt loam, a soil from Northeast Utah, was used for experimental work on adsorption competition. The portion used was the size range less than 0.991 mm diameter. The physical-chemical analysis of an homogeneous portion of this soil, hereafter referred to as simply Mendon silt loam, is given in Appendix H. Prior to use, the soil samples were soaked in distilled water and autoclaved for 15 minutes at 121 C. Mendon silt loam was chosen for the bacterial adsorption study since pilot experiments using this soil showed significant cell uptake.

Silica sand. Silica sand (SiO_2), a coarse fraction of soil with no net charge and with very low chemical adsorption capacity was also studied. Particle size range was from 0.1 mm to 1.0 mm diameter.

Competitive sorbates

Sodium chloride (NaCl), sodium lauryl sulfate (SLS) and peptone were chosen to study their competitive effect on bacterial adsorption. They represent different categories of chemicals which may be found in contaminated waters flowing through the soil and in other situations involving a bacteria-soil-chemical species-water contact opportunity. NaCl represents an inorganic group of chemicals and is a major component of sewage; sodium lauryl sulfate, $C_{11}H_{23}COOSO_3Na$, is a synthetic detergent, and peptone represents organic matter, specifically degraded protein. A definite chemical structure and formula for peptone is not possible since it is composed of a mixture of many types of short soluble peptide chains and amino acids.

When two sorbates, A and B are competing for sorption sites, A may inhibit the adsorption of B. The threshold concentration level of A at which this occurs significantly, is here referred to as the "threshold competitive level" of A. To determine threshold competitive levels of NaCl, SLS and peptone, the concentration of each given sorbate (alone) was increased in the presence of bacteria and soil to the point that measureable bacterial inhibition to adsorption was discerned. This was the point designated as the threshold competitive level.

Since the filter assay method depends on viable cells, the question arose whether the chemicals used as competitive sorbates might be toxic to *S. aureus.* In order to clarify this point, several toxicity experiments were conducted, using various concentrations of chemicals and bacterial cells. This was done by stirring bacteria-chemical suspensions in an experimental flask in the absence of soil, and measuring the surviving bacterial concentration at regular intervals. Since it was necessary that the experiments be conducted below the threshold toxic levels of each of the chemical sorbates, an SLS concentration of .05 grams per liter was chosen for this study (Figure C-1, Appendix C) as was a peptone concentration of 3.8 grams per liter (Figure C-2, Appendix C). Although NaCl did not show significant competition with bacteria for adsorption at 27C (Figure C-9, Appendix C), three percent NaCl concentration was selected to determine the adsorption isotherms. Isotherms were determined at 10C, 20C, 27C, and 37C. Throughout these experiments, the initial cell concentration was held constant at 1×10^8 cells/ml. This concentration is in the flat portion of the bacterial adsorption isotherm, Figure 2.

Experimental procedure

Basically the three adsorbents were handled in much the same way although charcoal was used in smaller amounts, 1 gram per 100 ml of suspension, while the soils were used at 10 grams per 1800 ml of suspension. Each experiment was performed with one control to determine cell loss without adsorbent addition plus at least two or more flasks at a constant adsorbent level containing cells at various initial concentrations. The sorbate competition studies were accompanied by one other control, that of cells plus adsorbent without the competitive sorbate. A typical competitive experiment consisted of:

Flask I: Distilled water (1800 ml) + *S. aureus* (C_1)

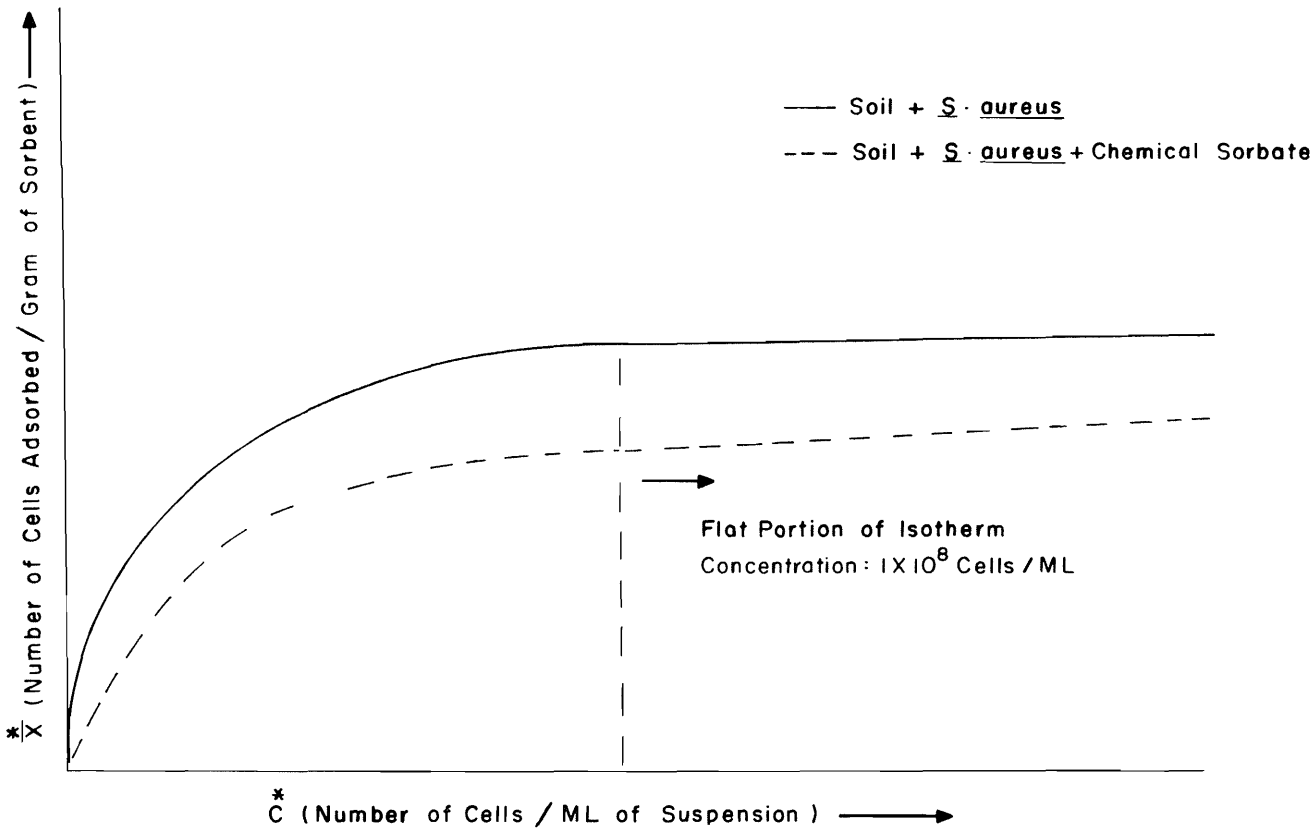


Figure 2. Theoretical bacterial adsorption isotherms with and without chemical competition.

Flask II: Distilled water (1800 ml) + *S. aureus* (C_1) + soil (10 g)

Flask III to V: Competitive sorbate + distilled water (1800 ml) + *S. aureus* (C_n) + soil (10 g)

in which

C_n represents initial cell concentrations C_1, C_2, and C_3.

Each flask contained a stir-bar and was placed on an air-driven magnetic stirring mechanism in a large refrigerated-heated thermostatically controlled water bath shown in Figure 1(a). Temperature variation was less than ± 0.1C during the course of an experiment, at any of the temperatures used. Isotherms were determined at 10C, 20C, 27C, and 37C, respectively, with the limits of viability of *S. aureus* controlling the working temperature range. Temperature equilibrium between the experimental flasks and the constant temperature water bath was obtained in about three hours. Therefore, it was necessary to keep the experimental flasks in the constant temperature water bath at least three hours before performing the experiment.

A bacterial suspension having a selected initial concentration was prepared. Stirring was initiated and the cells were then added to experimental flasks; stirring was of moderate intensity. Samples were taken from these flasks, before the addition of soil, to determine the initial cell concentrations in the respective flasks.

Ten grams of adsorbent suspended in 100 ml of distilled water were then added to each of the flasks (except the organism control). Stirring was halted at 5-, 15-, 30-, 45-, and 60-minute intervals, and the soil was allowed to settle to the bottom of the flasks for 30 seconds to three minutes depending on the adsorbent; a 1 ml sample from the supernatant of each flask was then taken. Samples were diluted according to the dilution scheme shown in Figure 3.

Calculations and plotting

Depletions and uptake. Bacterial colonies in the samples taken from the experimental flask at selected sampling intervals (at 0-, 5-, 15-, 30-, 45-, and 60-minutes) were counted. The number of bacteria remaining in the soil-bacteria suspension was plotted against the sampling time, which resulted in a depletion curve, Figure 4. The horizontal asymptote on this curve was taken as an equilibrium cell concentration in the solution phase, and was for convenience designated as C^* (cell/ml of

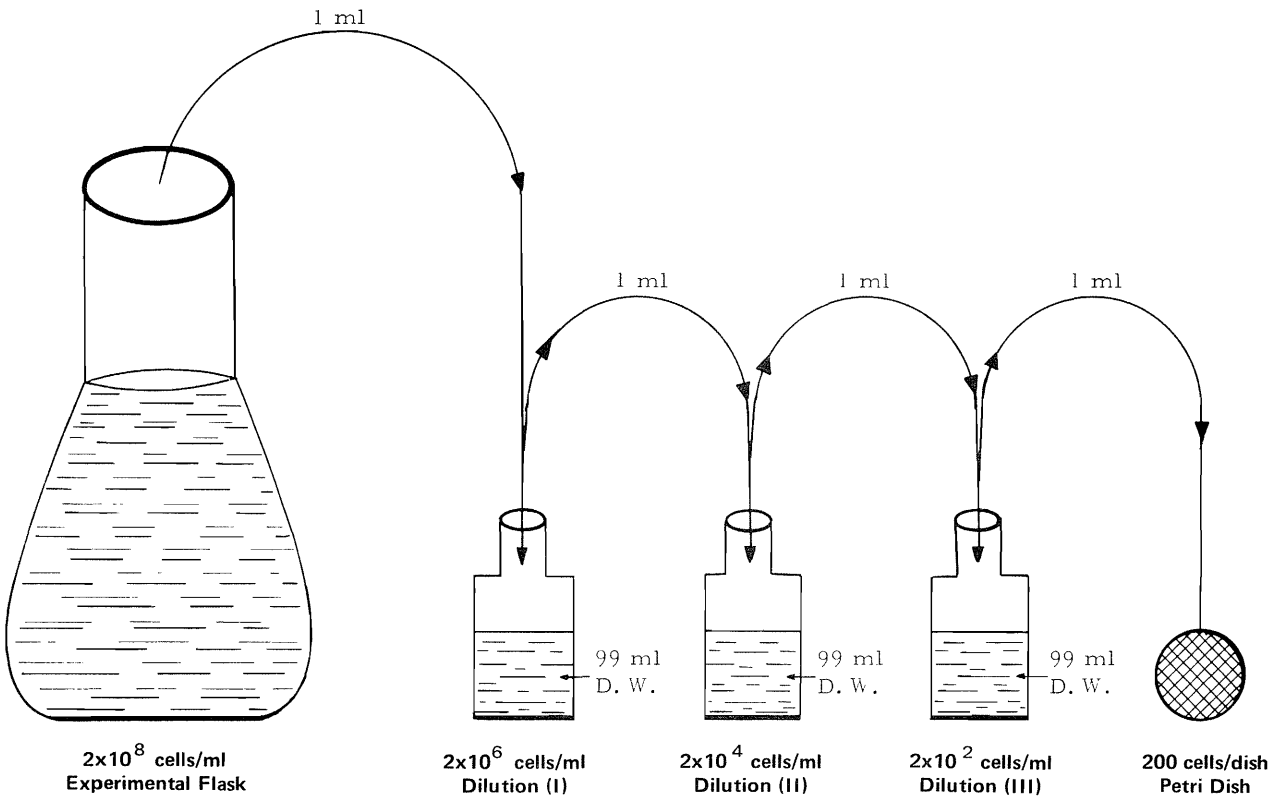


Figure 3. Diagrammatic illustration of the dilution scheme.

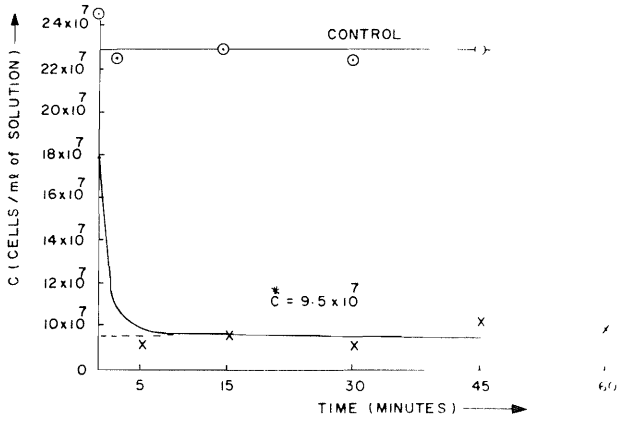


Figure 4. Depletion of bacteria with time from solution-sample: 10 grams of Mendon silt loam.

solution). The number of cells depleted from the soil-bacteria suspension was assumed to be adsorbed on soil. The number of bacteria adsorbed at selected sampling time was calculated using the following formula.

$$\overline{X} = \frac{(C_o - C)\ \text{cells/ml} \cdot \text{Volume-ml}}{\text{gm soil}}$$

in which

$\overline{X}$ = the number of cells adsorbed/gram of soil at a selected sampling time

C_o = the initial cell concentration (cells/ml)

C = the cell concentration at a selected sampling time (cells/ml)

The volume term refers to the total volume of the bacteria-soil-water suspension in the experimental flask. A plot of $\overline{X}$ vs. the sampling time was made which yielded a bacterial uptake curve, Figure 5. The horizontal asymptote on this curve was taken as an equilibrium cell concentration on solid phase, which for convenience was designated as $\overline{X}^*$ (cells/gram of soil).

Adsorption isotherms. An adsorption isotherm is, in graphical form, a plot of equilibrium concentrations of bacteria in solid and liquid phases, $\overline{X}^*$ and C^*, respectively. Each bacterial adsorption experiment provided a single point for defining an experimental isotherm. The locus of best fit for a number of such points obtained at a given temperature defines completely such an experimental isotherm. Such isotherms were obtained for

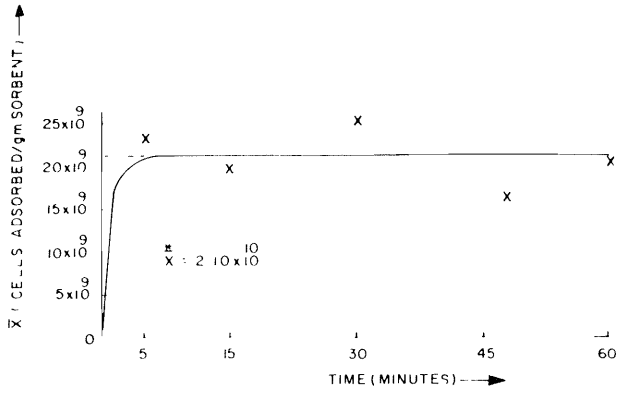


Figure 5. Uptake of bacteria with time on solid phase.

temperatures of 10C, 20C, 27C, and 37C, for all sorbate-sorbent systems studied.

The best fit curve for this locus of points was obtained by regression analysis of the Langmuir isotherm in linearized Equation (12).

Regression analysis of the set of experimental points was done by the computer programs listed in Appendix B. Appendix B also illustrates the numerical and graphical output from this program. The output from this computerized analysis of experimental points yields the Langmuir constants α and X_m. Figure B-15, Appendix B, shows a sample of a best fit linearized Langmuir isotherm, Equation (12). Figure B-16, Appendix B, shows the same experimental points plotted in the conventional form of the Langmuir isotherm, Equation (11). The curves drawn in Figures B-15, Appendix B, and B-16, Appendix B, were based upon the values of α and X_m shown in the printout, Figure B-14, Appendix B.

Enthalpy (ΔH°), entropy (ΔS°), and energy (ΔF°) of standard state. In order to evaluate the standard state enthalpy, ΔH°, a plot of log α versus reciprocal of absolute temperature was made in accordance with Equation (18). As indicated in Equation (18), the slope of such a plot is $-\Delta H^\circ/2.3R$, which will then yield enthalpy change of defined standard adsorption reaction, ΔH°. After determining ΔH°, the standard state enthalpy (ΔS°) and standard state free energy (ΔF°) were calculated using Equations (20) and (13), respectively.

Data processing

All experimental data were recorded on IBM coding sheets, punched on cards, and processed by computer programs developed for this purpose. This was done for two reasons. First, such processing facilitated retrieval and analysis of large quantities of data at any stage of processing whether as initial raw data or in some processed form. The manner of cataloging the data and the results and the format for display of each, in printed and graphical form, insured this. Second, such processing eliminated large quantities of manual calculation, which released labor for other tasks and minimized chances for mistakes in data processing.

The complete data processing consisted of two phases described as A and B below:

A. Processing of bacterial depletion data.
   1. Bacterial depletion data were recorded on IBM coding sheets as indicated in Figures B-3 and B-4, Appendix B.
   2. These data were punched on IBM cards.
   3. The data cards were processed by the program BACTXT using the Univac 1108 computer. The card arrangement is shown in Figure B-1, Appendix B.
   4. The output from program BACTXT consisted of:
      a. Tabular output designated as "Table 2" (Appendices) which shows all experimental conditions, depletion data as recorded, and calculated values of $\overline{X}$ and C. Figure B-6, Appendix B, is a sample output for one "run."
      b. Plotted points in graphical form showing the bacterial uptake with time as illustrated by Figure B-7, Appendix B. The horizontal asymptote of this curve yielded a value of equilibrium cell concentration in solid phase, $\overline{X}^*$.
      c. Plotted points showing the bacterial depletion with time, Figure B-8, Appendix B. The horizontal asymptote of this curve resulted in a value for equilibrium cell concentration in solution phase, C^*.

B. Processing of equilibrium data.
   1. The equilibrium data obtained from 4b and 4c were recorded on another IBM coding sheet as indicated in Figure B-12, Appendix B.
   2. These data were punched on IBM cards.
   3. The data cards were processed by the program ALPHAB, again by the Univac 1108. The card arrangement is shown in Figure B-11, Appendix B.
   4. The output of program ALPHAB consisted of:
      a. Tabular output, Figure B-14, Appendix B, showing the numerical values of α, X_{max}, R, and R^2.
      b. Graphical output showing equilibrium data and the best fit regression curves in the form of linearized Langmuir and conventional Langmuir isotherms, Figures B-16 and B-15, Appendix B, respectively.

These programs are described in detail in Appendix B.

Column experiments

Based on results of the adsorption experiments two materials were selected for column adsorption; sand for its complete lack of adsorption capacity and charcoal for extremely high adsorption capacity (see results). Figure 6 is a photograph of the experimental set up.

A glass tube, 22 mm internal diameter and 15 cm long, was carefully packed to a depth of 10 cm over a thin layer of glass wool held on a rubber stopper with one central hole. In the case of sand, this amounted to 85 gm of adsorbent and 20 gm for the charcoal. A glass tube with connected rubber hose and screw clamp was attached through the hole in the bottom stopper and an aluminum foil cone placed around the hose. This last was designed to minimize air currents while taking a sample from the rubber tube orifice.

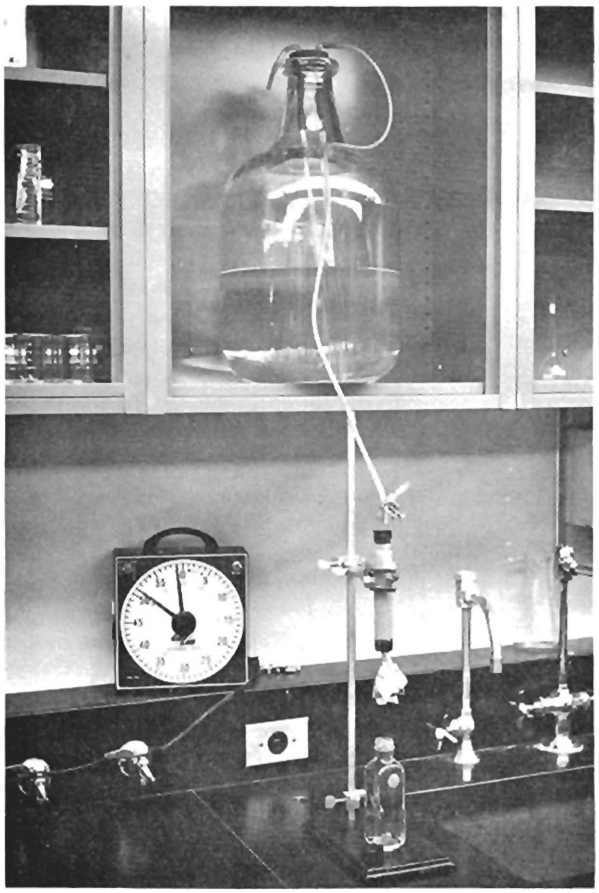


Figure 6. Column experiment apparatus.

A rubber stopper with two glass tubes was placed in the top of the column. One served as an air pressure release valve (with a screw clamp) and the other was attached to a large Marriot siphon reservoir. Column and reservoir were then autoclaved.

Distilled water was sterilized separately and added to the reservoir to a 20 liter volume. The water was then percolated through the column and the flow rate adjusted to 15 ml per minute. The water used in establishing the flow rate was replaced with sterile water. Enough of a previously sterilized NaCl solution was added to give a concentration of 300 mg/l and enough of a suspension of *S. aureus* cells was added to give a final concentration of about 300 per ml. Percolation was started.

Fifteen ml samples were collected in sterile flasks at various time intervals, the rest of the flow was collected in a separate container for disposal. One milliliter portions of the samples were then passed through membrane filters and handled as before. Samples were also taken at the termination of the experiment with sterile syringes and needles from the surface, the adsorbent-water interface and approximately 0.5 cm below the interface of the adsorbent to determine if a concentrated surface film may have built up during percolation.

A model was designed for predicting behavior in the columns with these two adsorbents. Program and sample output will be found in Appendix I. This model assumes that all sorbate particles that collide with sorbent particles stick upon collision. Thus we idealize the system to say that uptake to the adsorbed phase depends only upon rate of convective delivery (we ignore dispersion here in this cursory treatment) to the sorption sites and not upon the ability of the sorbent particle to accept the sorbate. This rate of delivery depends not only on the sorbate feed concentration and flow rate, but upon the probability of collision with a soil particle. The distance a sorbate particle must travel to experience such a collision is a characteristic of the porous media. This means the sorbate concentration will decay with distance in an exponential manner. The program, Figure I-1, Appendix I, provides the complete algorithm and further explains the logic of this procedure. A discussion by Hendricks (1965) further elaborates this method. The result of this program is only an approximate limit assuming no particle rejection on impact. A more realistic model would consider uptake kinetics as well—such as a second order rate law with respect to sorbate concentration and sorbent sites available. Figure B-7 and similar data would be the basis for such a kinetic analysis.

RESULTS AND DISCUSSION

Summary

Three categories of results are reported; these include: (1) direct microscopic observations of bacterial adsorption, (2) thermodynamic analysis of adsorption measurements, and (3) column breakthrough experiments. The bulk of our effort was directed toward category (2), the primary concern of this investigation.

Direct microscopic observations

In addition to quantitative viable measurements of bacterial adsorption, we also have observed bacterial adsorption directly on activated carbon and kaolinite clay.

Activated carbon. Figure 7 is a color photograph showing dead *S. aureus* cells attached to a particle of activated carbon (Calgon, Filtrasorb 400). The adsorbed cells are seen as fluorescing red cocci; they are located by the guide marks at the bottom and left margins of the photograph. Figure 8 is a black and white further enlargement of the same photograph; again the cocci are located by guide marks (at the bottom and left margins, respectively) with cells seen as small white circles. The adsorbate cells shown were killed (by heating) and stained with acridine orange prior to contact with the charcoal particles. Viable cells were also observed attached to activated carbon particles but photographs were not successful due to Brownian movement. The first experiments consisted of:

(1) Harvesting and suspending cells in 0.1% acridine orange;
(2) Removing excess dye by repeated centrifugation in distilled water at 12,000 rpm in a Sorvall high speed centrifuge;
(3) Suspending the stained cells in the presence of activated charcoal as usual and mixing until equilibrium was established;
(4) Removing samples of charcoal particles and placing on Vaseline ringed wet mount slides;
(5) Observing under ultraviolet light with a Zeiss fluorescence microscope.

Acridine orange enters the cell and interacts with the DNA of the cell. If the cell is living, only a small amount enters and the cell fluoresces green. If the cell is dead, more dye enters and causes the cell to fluoresce red. Both green and red cells were clearly seen to be attached to the surface of the carbon in numerous locations. Dead cells seemed to adsorb as well as live ones. The preparation used to make the photograph for Figures 7 and 8 was dried to eliminate the problem of Brownian movement but the pictures are illustrative of the visual observations made with wet mounts.

Kaolinite clay. Direct observations on the bacteria-clay combination using phase contrast were made with the wet mount method. Again Brownian movement interfered with photography. However, adsorption and desorption were observed to occur while under observation. These observations are summarized in Figure 9. One interesting observation was that cells appeared to accelerate their movement toward or away from a clay particle when desorbing (the latter case) or adsorbing (the former case) suggesting that adsorptive forces may be strong enough to overcome Brownian motion when cells are within one cell diameter of the adsorbing site. Cells were observed to be only temporarily or more or less permanently attached to the clay particles. We were unable to predict when a particle would desorb again, which suggests that this is a strictly random occurrence with sorption and desorption balancing each other when equilibrium is reached. One could possibly speak in terms of attachment (or adsorption) half-life at equilibrium.

The conclusion of these experiments was, that bacteria do adsorb onto both charcoal and clay and in the case of charcoal, dead cells adsorbed apparently as readily as the live cells. With clay, adsorption and desorption could be observed directly.

Adsorption isotherms

Adsorbents. Four different adsorbents were used: (1) activated charcoal, (2) kaolinite clay, (3) Mendon silt loam, and (4) silica sand. The pertinent physical characteristics of each of these granular media are summarized in Table 1.

Conditions. The results of equilibrium measurements for the bacterial adsorption reaction are expressed in terms of isotherms. We determined isotherms for each adsorbent at four temperatures, 10C, 20C, 27C, and 37C. This temperature span is relatively narrow thermodynamically speaking; however, it represents the limits of viability of the organism used.

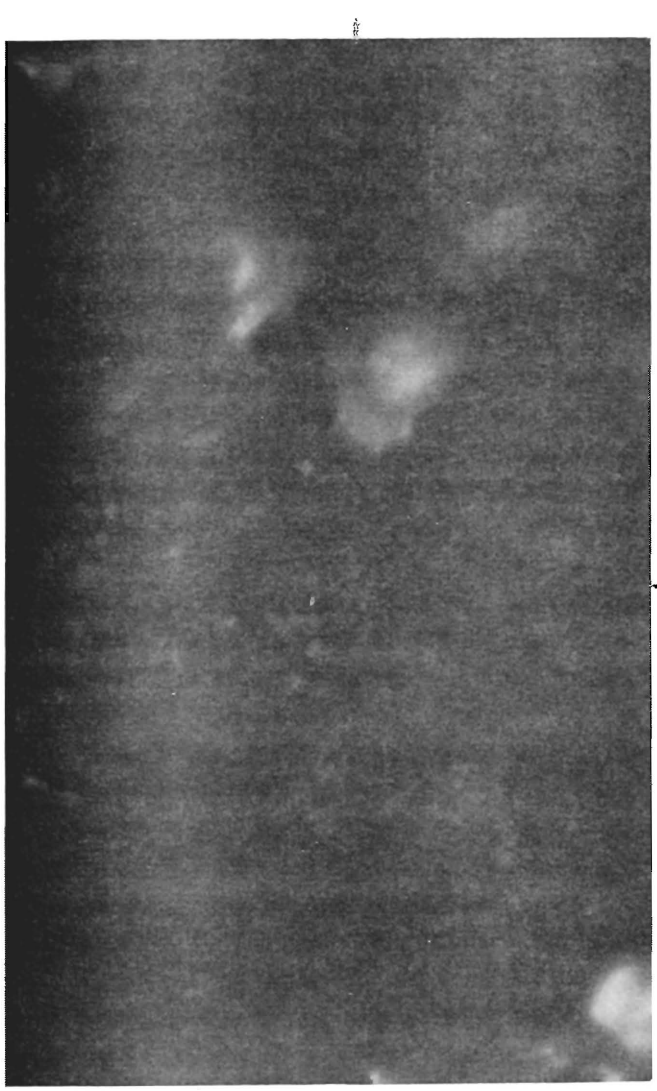


Figure 7. Adsorbed acridine orange treated *S. aureaus* on activated carbon as observed with fluorescence microscopy. Dead attached cells appear red. View picture so that marks on border are at left and bottom. Their intersection is the chief area of interest. Zeiss fluorescence automatic photomicroscope, 40X objective, Kodachrome 1135 mm. Enlargement of cell is 900X.

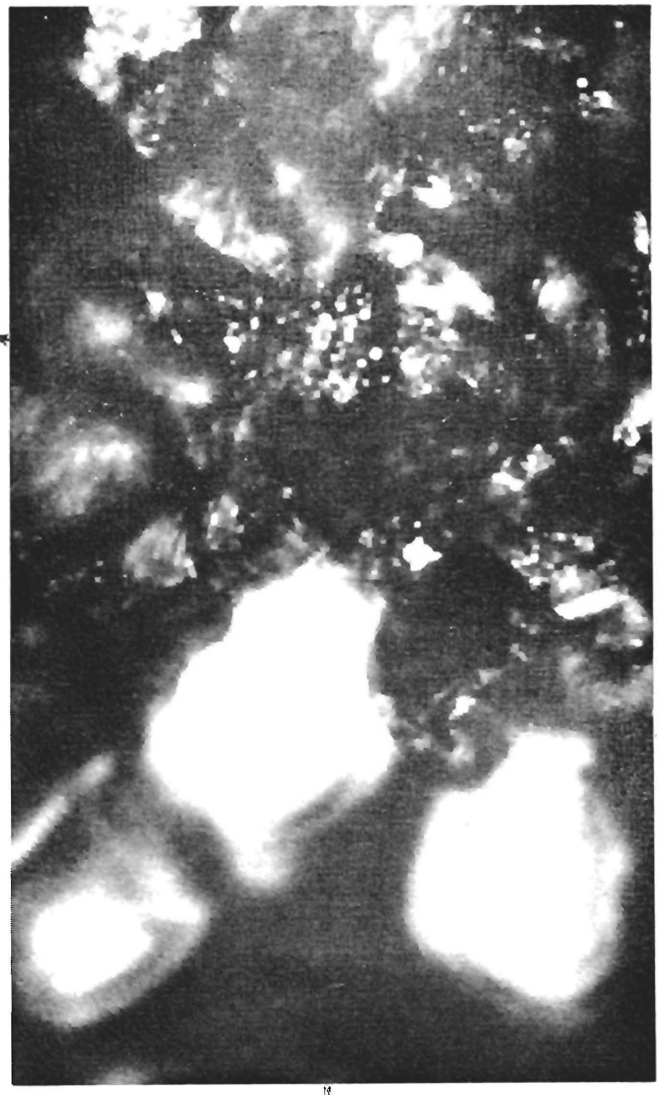
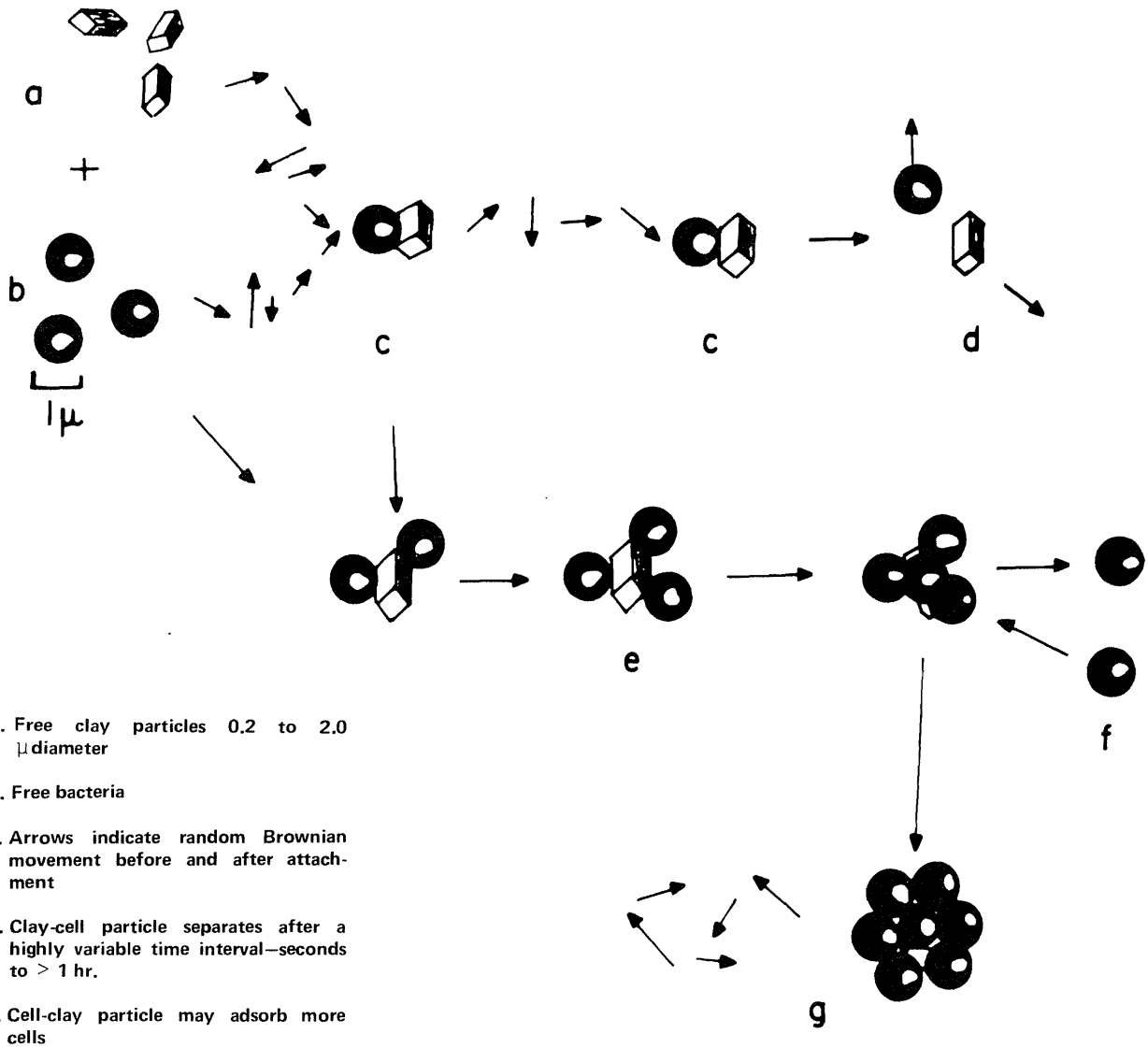


Figure 8. Black and white enlargement of the area of interest from the film of Figure 7. Intersection of border marks is the area of interest. When marks are at left and on bottom, the two photographs are oriented the same. Cell enlargement, 1500X.



a. Free clay particles 0.2 to 2.0 μ diameter

b. Free bacteria

c. Arrows indicate random Brownian movement before and after attachment

d. Clay-cell particle separates after a highly variable time interval—seconds to > 1 hr.

e. Cell-clay particle may adsorb more cells

f. Equilibrium established when cells leave and are adsorbed and desorbed at about equal rates over all particles

g. Entirely covered particles occasionally seen as were clay particles with no adsorbed bacteria.

Figure 9. Observations on cell-clay interaction in a wet mount.

Table 1. Characteristics of adsorbents.

Granular Media	Mean Particle Diameter (mm)	Range in Size (mm)	Surface Area (m^2/gm)	Cation Exchange Capacity (meq/100 gm)
Activated charcoal (Filtrasorb 400)	0.9	*	800-900	0.0
Kaolinite clay	.001	.0002-.004	12	2
Mendon silt loam	.01	See Appendix H	60-80	26.7
Silica sand	.53	.34-.73	.0055	0.0

*Uniformity coefficient less than 1.7.

We describe also the results of experiments conducted to ascertain the effect of chemical environment on the bacterial adsorption reaction, using three representative chemical categories: (1) sodium chloride, (2) peptone, and (3) sodium lauryl sulfate.

Isotherm results. Table 2 summarizes all of the sorbent-sorbate systems tested and the temperature condition and results of data analysis for each test. From these results, we make inference as to the effect of: (1) soil type, (2) the effect of chemical competition, and (3) the effect of temperature on the bacterial adsorption reaction.

Each isotherm which is reported in Table 2 is described in detail in Appendices D, E, F, and G in the sequence:

(1) computer output summarizing conditions of the experiment, the equilibrium data, and the results of regression analysis of the equilibrium data to find α and X_m
(2) the conventional Langmuir isotherm plot, as generated by the Gerber plotter program, showing the equilibrium data and the best fit Langmuir isotherm
(3) the linearized plot of the Langmuir isotherm, as generated by the Gerber plotter program, showing transformed equilibrium data and the best fit regression line.

The α and X_m values given in Table 2 were abstracted from the isotherm computer output tables in Appendices D, E, F, and G. The α values in Table 2 are in different units than the "ALPHA" values given in the Appendices. Values for α, Table 2, are in liter/mole of cells while computer regression analysis, Appendices D, E, F, and G, gives ALPHA in ml/cell. The conversion is achieved as follows using activated charcoal at 10 C, Figure D-1, Appendix D, as the example for the sample calculation:

$$\text{ALPHA} = .134350\times10^{-6} \text{ ml/cell}$$
(Figure D-1, Appendix D)

$$\alpha = .134350\times10^{-6} \text{ ml/cell} \times 6.023\times10^{23} \frac{\text{cells}}{\text{mole}} \times \frac{1 \text{ liter}}{10^3 \text{ml}}$$

$$= 0.807\times10^{14} \text{ liter/mole of cells}$$
(Table 2)

These differences in α and ALPHA units are very important and are subtle enough to be missed unless explicitly pointed out. For use in thermodynamic functions the liter per mole expression is necessary in order to be consistent with units in the usual thermodynamic expressions where concentrations are expressed in moles per liter. Bacterial concentrations are usually expressed, however, in terms of cells per ml. With the liter/mole expression, equilibrium appears overwhelmingly to the right; in the ml/cell expression, equilibrium is overwhelmingly to the left. Thus one can be grossly misled in interpreting the equilibrium constant unless also cognizant of the role of units.

Comparison of isotherms. It is interesting to note that all nonzero α values in Table 2 are in the same general logarithmic range—from 10^{12} to 10^{15} liter/mole. The X_m values compare within two logarithmic cycles—from 10^{10} cells/gm for activated charcoal to 10^{12} cells/gm for kaolinite. X_m in cells/gm is not compatible with α in liter/mole for calculations involving equilibria.

The R^2 values shown in Table 2 are very high; in fact 10 of the isotherms are fitted to data having a

Table 2. Bacterial adsorption experimental results.

Sorbent	Sorbate(s)	R^a	R^{2a}	T (^oC)	$\frac{1}{T} X10^{-3}$ ($^oK^{-1}$)	X^a_m (cells/gm)	α^e (liter/mole)	$\Delta H^{o\,b}$ (kcal-mole^{-1})	$\Delta S^{o\,c}$ (e.u.)	$\Delta F^{o\,d}$ (kcal-mole^{-1})
Activated carbon (Filtrasorb-400)	S. aureus	0.902	0.813	10	3.55	$0.450X10^{10}$	$0.807X10^{14}$	9.80	97.0	-17.6
		0.897	0.805	20	3.41	$0.615X10^{10}$	$0.112X10^{15}$			-18.6
		0.913	0.834	27	3.33	$0.498X10^{10}$	$0.625X10^{15}$			-19.3
		0.980	0.960	37	3.24	$0.848X10^{10}$	$0.350X10^{15}$			-20.2
Kaolinite clay	S. aureus	0.548	0.300	10	3.55	$0.414X10^{12}$	$0.104X10^{14}$	3.60	72.0	-16.8
		0.844	0.712	20	3.41	$0.422X10^{12}$	$0.120X10^{14}$			-17.5
		0.785	0.616	27	3.33	$0.475X10^{12}$	$0.120X10^{14}$			-18.2
		0.797	0.636	37	3.24	$0.330X10^{12}$	$0.214X10^{14}$			-18.7
Mendon silt loam	S. aureus	0.035	0.001	10	3.55	$0.110X10^{11}$	$3.10\ X10^{13}$	8.50	92.0	-17.5
		0.980	0.961	20	3.41	$0.149X10^{11}$	$5.10\ X10^{13}$			-18.5
		0.766	0.587	27	3.33	$0.200X10^{11}$	$8.00\ X10^{13}$			-19.1
		0.996	0.992	37	3.24	$0.280X10^{11}$	$10.00\ X10^{13}$			-19.9
Mendon silt loam	S. aureus + Na-lauryl sulfate	0.00	0.00	10	3.55	0.00	0.0	3.72	79.0	---
		0.950	0.903	20	3.41	$0.105X10^{11}$	$2.13\ X10^{14}$			-19.4
		0.829	0.687	27	3.33	$0.916X10^{10}$	$2.44\ X10^{14}$			-20.0
		0.945	0.892	37	3.24	$0.154X10^{11}$	$2.74\ X10^{14}$			-20.8
Mendon silt loam	S. aureus + Peptone	0.00	0.00	10	3.55	0.00	0.0	24.0	145.	---
		0.986	0.972	20	3.41	$0.110X10^{10}$	$1.48\ X10^{14}$			-18.5
		0.879	0.772	27	3.33	$0.204X10^{10}$	$0.715X10^{14}$			-19.5
		0.993	0.985	37	3.24	$0.131X10^{10}$	$4.60\ X10^{14}$			-21.0
Mendon silt loam	S. aureus + NaCl	0.737	0.543	10	3.55	$0.238X10^{11}$	$3.12\ X10^{12}$	23.0	138.0	-16.0
		0.982	0.983	20	3.41	$0.909X10^{10}$	$5.45\ X10^{13}$			-17.5
		0.818	0.669	27	3.33	$0.738X10^{11}$	$2.25\ X10^{13}$			-18.5
		0.979	0.959	37	3.24	$0.942X10^{10}$	$4.75\ X10^{13}$			-19.7
Silica sand	S. aureus	0.0	0.0	10	3.55	0.0	0	-	-	+ ∞
		0.0	0.0	20	3.41	0.0	0	-	-	+ ∞
		0.0	0.0	37	3.24	0.0	0	-	-	+ ∞

[a] Calculated by regression analysis using the linear transformation of Langmuir isotherm: $\left(\frac{C^*}{X^*} = \frac{1}{\alpha X_m} + \frac{1}{X_m} \cdot C^*\right)$, Equation (12)

[b] Evaluated by measurement of slope of the experimental plot for: $\log\alpha = -\frac{\Delta H^o}{2.3R} \cdot \frac{1}{T} + \frac{\Delta S^o}{2.3R}$, Equation (20)

[c] Obtained from y-axis intercept at $1/T = 0$, Figures 9 - 14, respectively.

[d] Calculated by equation, $\Delta F^o = \Delta H^o - T\Delta S^o$, Equation (19), using values of T, ΔH^o, and ΔS^o in this table. Equation (19)

[e] Values given for α are in liter/mole of cells; computer regression analysis in Appendix D gives α in ml cell: the conversion is achieved as follows: using activated charcoal at 10^oC as an example: $\alpha' = .134350X10^{-6}$ ml/cell, Appendix D, Figure D-1, $\alpha = .134350X10^{-6}$ ml cell X $6.023X10^{23}$ cells mole X 1 liter/10^3 ml = 0.807×10^{14} liter/mole of cells.

regression coefficient greater than 0.90. This is almost remarkable in view of the results we had anticipated for the equilibrium experiments; we were not confident that the membrane technique of counting bacteria would yield such results.

Two of the systems in Table 2, Mendon silt loam + Na-lauryl sulfate and Mendon silt loam + peptone, showed zero adsorption at 10C. We have no explanation for this anomaly and can only report it. Sufficient testing was done at this temperature for both systems to verify this observation. Data are shown in Figures E-1, E-2, and E-3, Appendix E, and Figures F-1, F-2, and F-3, Appendix F, respectively.

One system, silica sand, showed no adsorption. Testing at three temperatures was felt exhaustive enough to definitely establish this fact. This could be due to: (1) insufficient bonding energy, or (2) surface area too low for favorable equilibrium.

Though activated charcoal has a very large surface area as shown in Table 1, there may be some question as to how much of this is available to the bacteria, since their size is about 1 μ and much of the surface area of charcoal is in pores of smaller diameter.

Thermodynamic functions

Evaluation from data. Utilization of the set of Langmuir alpha constants with the van't Hoff equation, Equation (20), is the basis for finding the standard enthalpy of reaction, ΔH°. Thus if we plot values of α against temperature in the form log α vs. 1/T, we would expect a straight line relation, assuming ΔH° is constant over the temperature span of interest. Figures 10-15 show such plots for each of the Table 2 systems —except silica sand, which did not adsorb bacteria. Standard state entropy of reaction, ΔS°, and standard state free energy of reaction, ΔF°, can be calculated then as indicated in Table 2 by footnotes.

Errors. Two observations concerning Figures 10-15 are important. First, the experimental temperature span of 10-37C is very narrow for thermodynamic work. Curve fittings to experimental points are much more sensitive to errors with such narrow temperature bands. Second, only four data points are used in fitting the curves. Since the range in temperature could not be any greater due to cell viability, and since each point represents an isotherm, and as such involves considerable effort to define, we are probably at the point of diminishing marginal returns with the data available.

Two of these figures show remarkable consistency; these are Figures 12 and 13. In the other figures the trends in slope are unmistakably negative, but the scatter in points raises some doubt as to the position of the best fit curve. The Table 2 values are derived from "eye" fits as represented by the solid lines in Figures 10-15. To put the

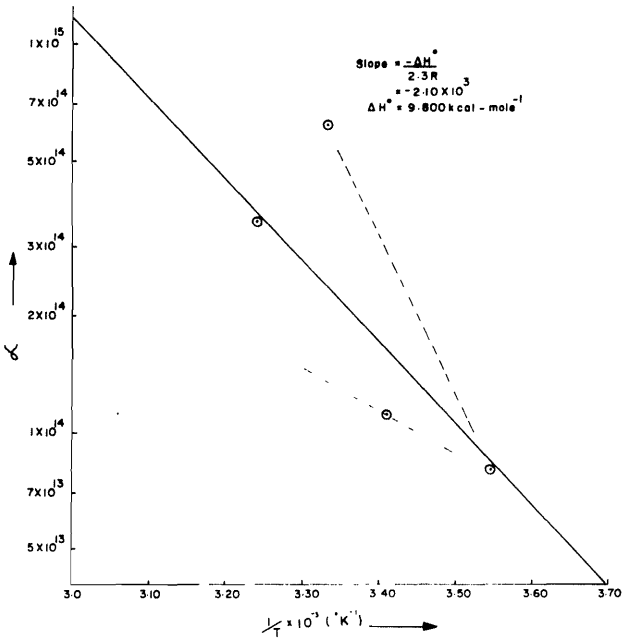


Figure 10. Evaluation of standard state enthalpy, ΔH°, for activated carbon-*S. aureus* adsorption system using van't Hoff's equation.

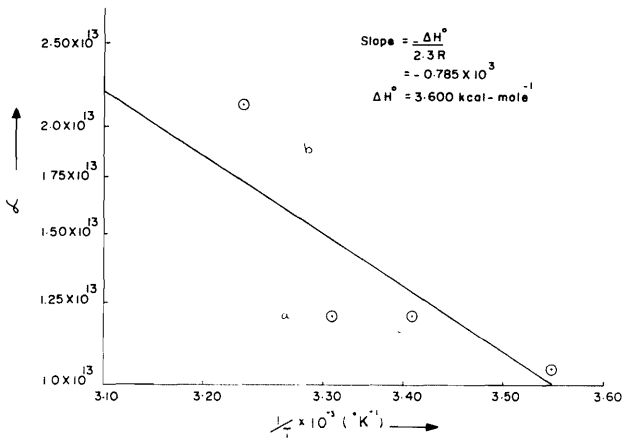


Figure 11. Evaluation of standard state enthalpy, ΔH°, for kaolinite clay-*S. aureus* adsorption system using van't Hoff's equation.

range of uncertainty in a little better perspective, the dashed lines "a" and "b" were drawn to represent the lower and upper bounds enveloping the possible fits using the four data points. The values of the thermodynamic functions resulting from the envelope boundaries are given in Table 3. The ΔF° values in Table 3 range from 18-20 kcal/mole with but two exceptions; this is interesting in view of the span of the envelopes in most cases. It is

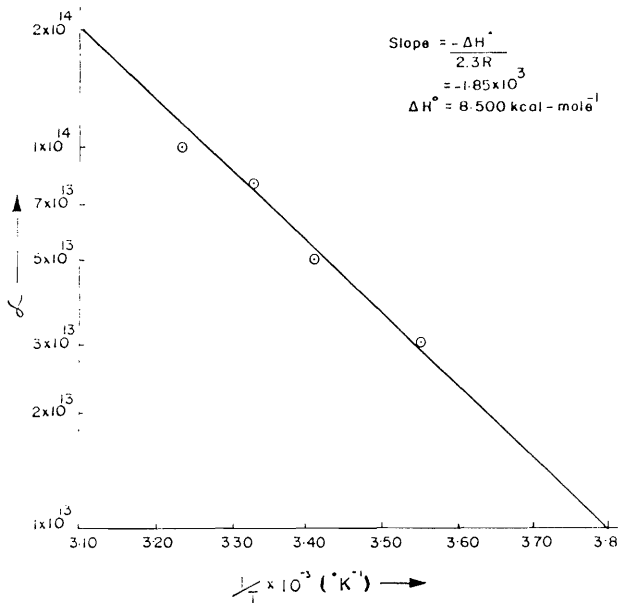


Figure 12. Evaluation of standard state enthalpy, ΔH°, for Mendon silt loam-*S. aureus* adsorption system using van't Hoff's equation.

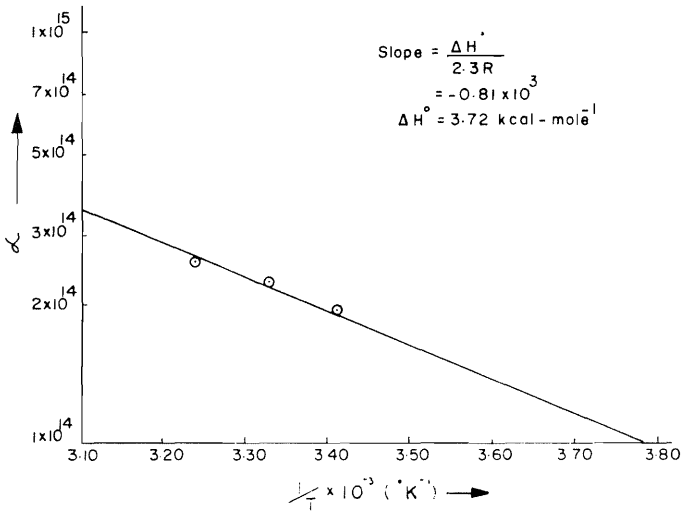


Figure 13. Evaluation of standard state enthalpy, ΔH°, for Mendon silt loam-*S. aureus*-Na-lauryl sulfate system using van't Hoff's equation.

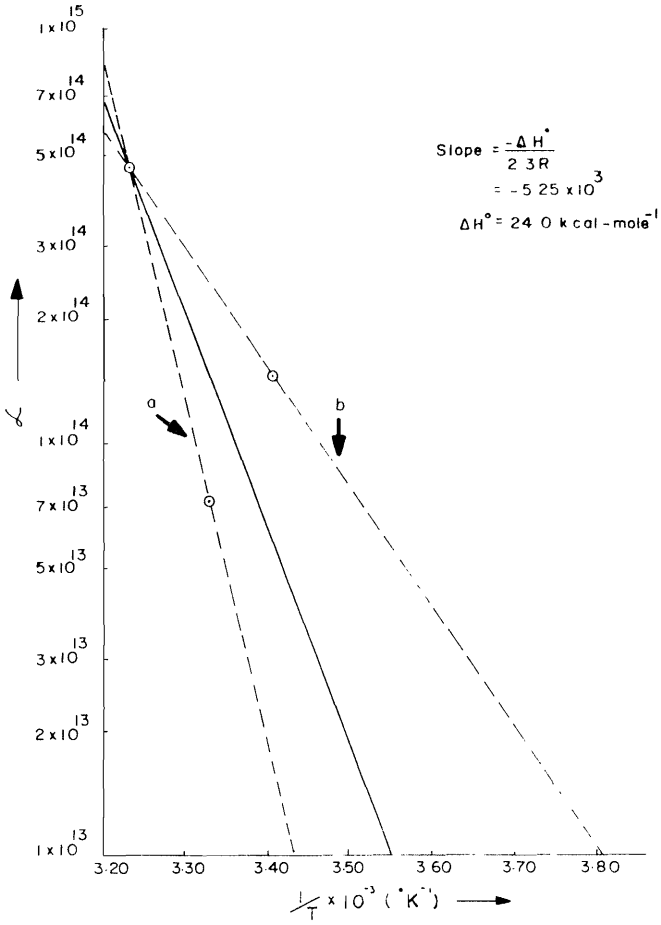


Figure 14. Evaluation of standard state enthalpy, ΔH°, for Mendon silt loam-*S. aureus*-peptone system using van't Hoff's equation.

difficult to make definitive statements in comparing the influences of soil type and chemical effects because of the span of the envelopes. We can have confidence, however, that the values reported are probably in the correct logarithmic range—which is significant. Also the "nominal fits," reported in Table 2 probably represent *trends* though we would not wish to risk the hazard of reading too much into the differences in ΔH° and ΔS° reported. Despite deficiencies it appears to us remarkable that thermodynamic functions can be defined even as well as indicated in Figures 10-15 and Table 3, in view of some of the uncertainties concerning counting techniques and whether bacterial adsorption did indeed take place.

Interpretation of thermodynamic values

It is important to realize that all thermodynamic values reported in Table 2 are for the whole adsorption reaction, as hypothesized in Equation (6) and Equation (27) respectively. These values are the same order of

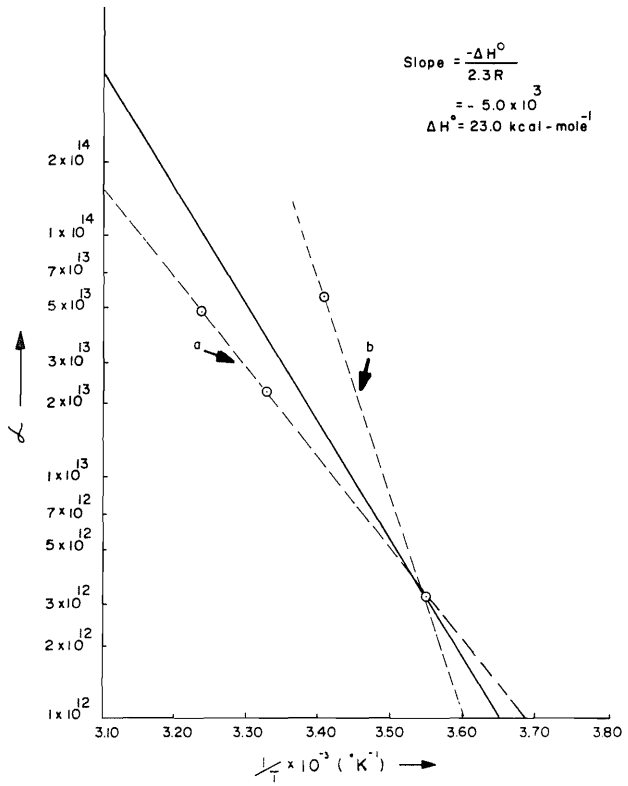


Figure 15. Evaluation of standard state enthalpy, ΔH°, for Mendon silt loam-*S. aureus* NaCl adsorption system using van't Hoff's equation.

magnitude as for an ordinary chemical reaction (i.e. kilocalories/mole). We cannot, however, accept the Table 2 values without further interpretation. First, it is clear from the negative ΔF° values that equilibrium is to the right—in favor of adsorption. Second, the positive ΔH° values indicate the reactions are, in all instances, endothermic; the peptone and NaCl competitive tests are more strongly endothermic than the rest. Again this must be interpreted in terms of the whole reaction, and not just for the bacterial adsorption. We see another interesting aspect of thermodynamics in the entropy term; the entropy of reaction, ΔS°, is, in every case, positive. Thus, it is the entropy of the reaction that provides the driving force for the reaction. In addition, the large orders of magnitude of the thermodynamic functions may or may not mean that the bacteria, per se, act with the same degree of drive. We can see this by examining the sets of partial reactions, Equations (3)-(5) and Equations (24)-(26), respectively. These equations show the importance of the solvent effect and the thermodynamic functions ΔH° and ΔS° must reflect the dehydration effect. The chemical competition of other adsorbates can be evaluated by comparing the ΔH° values for the Mendon silt loam system.

Competitive adsorption

The effect of the three chemicals, sodium-lauryl-sulfate, peptone, and sodium chloride, on bacterial adsorption using Mendon silt loam, can be seen by examining Tables 2 and 3 respectively. However, we should be cognizant that the thermodynamic functions

Table 3. Thermodynamic functions of upper and lower envelope boundaries of van't Hoff's plots.[a]

	Best estimate fit[b]			Lower bound[a]			Upper bound[a]		
	ΔH°	ΔS°	ΔF° 37C	ΔH°	ΔS°	ΔF° 37C	ΔH°	ΔS°	ΔF° 37C
Activated Carbon	9.80	97	-19.	4.75	81	-19.2	19.0	132	-19.5
Kaolinite Clay	3.60	72	-18.	1.62	119	-34.1	11.5	100	-18.5
Mendon silt loam	8.50	92	-19.	8.50	92	-19.0	8.50	92	-19.0
Mendon silt loam + Na-lauryl-SO_4	3.72	79	-19.	3.72	79	-19.0	3.72	79	-19.0
Mendon silt loam + peptone	24.0	145	-20.	12.8	107	-19.2	35.6	190	-18.4
Mendon silt loam + NaCl	23.0	138	-19.	19.1	125	-18.4	41.5	150	- 3.5
Silica sand			$+\infty$			$+\infty$			$+\infty$

[a] Figures 10-15, respectively.
[b] Table 2.

and α are psuedo values as suggested by Equation (37), since these calculations consider the bacteria-soil reaction, Equation (2), only. This should be kept in mind in subsequent interpretations. Examining Table 2, we see that ΔF°, and consequently α, shows no difference resulting from chemical competition. Also the more extreme analysis presented in Table 3 shows all ΔF° values to be in the same narrow band of 18.4 - 20.0 kal/mole—with one exception. The ΔH° and ΔS° values show differences caused by the three chemical competitors, however, we cannot make any conclusions with regard to the effect of chemical competition on bonding energies from the differences in ΔH° values, because we would first need to isolate the separate ΔH° values for the partial reactions, Equations (24)-(26).

In the competition experiments using Mendon silt loam above, Table 2, as the base, the chemicals chosen for study seemed to have an influence on bacterial adsorption. The maximum uptake of bacteria in cells per gram of soil (X_m) appeared to be little affected, if at all, by NaCl or by Na lauryl sulfate while peptone reduced the uptake by approximately a factor of ten. With peptone and Na lauryl sulfate, uptake at 10C is reported as zero. However, there was some indication that uptake did take place, at least with peptone, if the initial concentration of bacteria was reduced 10-100 times below the level normally used in the experiments reported in Table 2. Peptone very likely behaves in much the same fashion as the bacterial cell itself. Both contain positively and negatively charged areas and presumably compete for the same sites on the charged soil particle surface. This has been alluded to in the literature by several investigators, particularly Cookson and North (1967) who used peptone to desorb virus particles, also large protein complexes, from activated carbon.

Support for the idea of competition between peptone and *S. aureus* is also indicated in Figure C-4, Appendix C, which clearly shows that increasing peptone concentration interfers progressively with bacterial uptake.

The effect of Na lauryl sulfate is not quite as clear, complicated by the considerable toxicity (Figure C-1, Appendix C) of this surface activant. The results presented in Table 2 are suggestive of competition but could be due to other factors. The report of Roebeck et al. (1962) indicates no change in movement of coliforms in the presence of ABS; however, their use of peptone which permitted growth of the organisms as well as competitive adsorption, complicates interpretation of the adsorption phenomenon since this could result in growth of bacteria and plugging at the column origin.

Sodium chloride (Figure C-5, Appendix C, and Table 2) does not have a competitive effect based on X_m. Apparently the NaCl molecule and the bacterial cell do not compete for the same sites. Increasing concentration (at least to the point of toxicity) does not reduce bacterial uptake by soil nor does it appreciably reduce X_m.

In some ways the interaction between soil, bacteria and chemical behaves as a chromatography column.

The practical effect of this competition is that certain chemicals should enhance movement of bacteria through soil by competing for the normal adsorption sites and releasing bacteria for forward movement. Peptone would be an example of such a chemical. However, peptone as a model chemical has the additional complication of being metabolized by the bacteria causing a loss of chemical and a simultaneous increase in cell number *at the point of metabolism* which would introduce another physical process—filtering or plugging by the increased cell mass. Sodium lauryl sulfate might have a similar (but smaller magnitude) effect but its toxicity complicates its study by the methods used here.

Cell shape and motility may also have an effect. This study used a non-motile spherical coccus of about $1.0\mu \pm 0.2\mu$ diameter with a small range of variation. Elongation of the cell into the rod form increases the length width ratio as well as the variation range in length (diameter range would be about the same). The influence of motility (purposeful direction) should also have an effect as motile bacteria have been shown to be chemotactic and would tend to congregate at a point of nutrient surplus.

Column experiments

Results of the column experiments are presented in Table 4; for comparison the results of the simulation of the experiment, using adsorption data from Table 2, are shown also.

Figures I-2 and I-3, Appendix I, are the computer outputs for simulation of the two column experiments for sand and charcoal respectively; experimental conditions simulated are summarized at the beginning of each output.

Table 4 shows the complete recovery of the feed concentration of the bacteria immediately and throughout the silica sand experiment, subject to normal variation in bacterial counting techniques. Since the batch tests showed zero uptake of bacteria, this corroborates the importance of adsorption as a mechanism of bacterial retention. Evidently any supposed mechanism of mechanical sieving or micro-sedimentation is nonexistent for this silica sand column.

Since charcoal is slightly coarser than silica sand, we would expect the same result if the adsorption process did not occur in charcoal. However, the results presented in Table 4 clearly indicate that retention does occur in flow of bacteria through activated charcoal. Therefore adsorption is evidently a prime mechanism in bacterial retention

Table 4. Results of column experiments and computer simulation with sand and activated charcoal adsorbents, 27C.

	Sand (count/ml)		Charcoal (count/ml)	
	Experimental measurement	Equilibrium model simulation	Experimental measurement	Equilibrium model simulation
carboy[a]	74	70	610	1000
surface[b]	78	70	630	1000
1 minute	82	70	100	42
2 minute	48	70	166	42
3 minute	50	70	218	42
4 minute	60	70	150	42
5 minute	115	70	163	42
10 minute	84	70	67	42
20 minute	78	70	170	42
40 minute	60	70	230	42
60 minute	40	70	312	42
2 hours	46	70	365	42
3 hours	52	70	360	42
4 hours	12	70	330	42
5 hours	25	70	310	42
6 hours	55	70	345	42
7 hours	25	70	345	42
surface[b]	48	70	615	1000
interface[c]	60	70	512	1000
0.5 cm depth[d]	48	70	930	∿800

[a]After inoculation.
[b]At surface of column.
[c]On adsorbent surface.
[d]0.5 cm below surface.

in flow through porous media. These results compare favorably with the bacterial results of Robeck et al. (1962) using much lower flow rates and longer columns and with the results using viruses reported by several authors (Drewry and Eliassen, 1968; and Cookson, 1970) and virus size particles (Filmer and Corey, 1966). This also contrasts with traditional concepts of macroparticle removal which attribute removal primarily to straining, sedimentation, or both. Our conclusion is that adsorption plays a more important role than either of these mechanisms in the soils and under the conditions of our study.

The discrepancy between the computer equilibrium model prediction and the experimental measurements in Table 4 is due to the type of kinetics assumed. We assumed "transport kinetics" and attainment of zone equilibrium for our model, merely as a first attempt for illustrating the limit of maximum retardance time and profile for the breakthrough curve. The model would be considerably improved by a more complete kinetic analysis of the adsorption uptake-time data, such as Figure B-9, as done by Hendricks (1965). However, this depth of analysis is beyond the scope of this work.

SUMMARY AND CONCLUSIONS

We have endeavored to learn something about the thermodynamics of the adsorption reaction for bacteria and soils and to ascertain the importance of adsorption as a mechanism of retention in the movement of bacterial suspensions through soils. Our work has shown the following:

1. Adsorption has been observed visually. Microscopic observations of both kaolinite clay and activated charcoal clearly show bacteria adsorbed onto surface sites and in the case of clay, desorption also was seen to occur. For kaolinite clay the adsorbed half-life at equilibrium was probably in terms of minutes.

2. The standard thermodynamic functions (ΔF°, ΔH°, ΔS°) for the bacterial adsorption reactions are energetically about the same magnitude (in kilocalories per mole) as those for many normal chemical reactions.

3. Langmuir isotherms can be defined for bacterial adsorption with a relatively high degree of statistical certainty. Coefficients of variation, R^2, for each isotherm were reasonably good (see Table 2). This was true despite the inherent uncertainty in determination of individual points in the bacterial depletion-adsorption experiments.

4. Conventional chemical thermodynamics can be applied to bacterial adsorption by soil particles. The usual thermodynamic functions for chemical reactions, ΔF°, ΔH°, and ΔS°, can be measured. Values obtained are probably "order of magnitude" in precision, however. This is due largely to the relatively narrow thermodynamic temperature range (10C to 37C), necessarily used, which accentuates sensitivity of ΔH° to the statistical uncertainty in α.

5. For those sorbents tested which show sorption (activated carbon, kaolinite clay, and Mendon silt loam), type of sorbent has little discernible effect on reaction thermodynamics. We use the order of magnitude interpretation of results in Tables 2 and 3 in arriving at this conclusion. Silica sand, however, showed no adsorption.

6. We speculate, comparing results using the three sorbents with appreciable surface areas (see Table 1) with silica sand which has negligible surface area, that surface area is a factor in adsorption of bacteria on granular particles.

7. Two of the three chemicals tested appeared to influence the thermodynamic functions ΔH° and ΔS° for the bacterial-chemical adsorption reaction, while the influence of sodium-lauryl-sulfate is not pronounced enough to be conclusive (Tables 2 and 3).

8. In testing the effect of three chemicals and one sorbent on adsorption of bacteria and also three additional sorbents alone, we found no apparent differences in ΔF° (Tables 2 and 3). Practically this means that permutations of the types used will not appreciably affect the equilibrium constant for the reaction and that the temperature effect can be discerned directly by Equation (13).

9. The equilibrium constant is sensitive to temperature change; the degree of sensitivity is given by the magnitude of the ΔH° term.

10. The bacterial adsorption reaction is endothermic as evident by the positive values of the ΔH° term. This effect is offset by the positive ΔS° values and thus it is the ΔS° that provides for a negative ΔF° which means favorable equilibrium in the direction of adsorption.

11. To compare the equilibrium values with chemical reactions, the units of alpha must be expressed in molar terms, liters/mole. We presume a mole of bacteria to be 6.023×10^{23} cells for purposes of these calculations.

12. It is quite hazardous to speculate about the mechanisms involved in the bacterial adsorption reaction. The thermodynamic functions derived from the data relate to the whole reaction, Equation (6). We are not sure about the proposed stoichiometry for this equation. The enthalpy and entropy changes for the solvated water in the partial reactions, Equations (3) and (4), could be significant.

13. Based upon results of Table 4 the predominant mechanism for bacterial retention in the columns tested is adsorption. We hypothesize also that, based upon thermodynamic analysis of other soil-bacteria non-flow systems, adsorption would be a predominant mechanism for any soils which exhibit negative ΔF° values on the order of kilocalories. This presumes no large activation energy for the reaction.

14. Based on the competitive adsorption portion of the study, bacterial adsorption should be decreased by certain chemicals (peptone and possibly Na lauryl sulfate) and movement through soil should be accelerated by these compounds provided other complicating factors are absent (metabolism in situ, chemotaxis, zoologeal mat formation). Other chemicals (NaCl) appear to have little or no effect on adsorption.

15. While bacterial adsorption is a real phenomenon of significant importance relating to travel of bacteria through soils, in practical situations other factors may be of greater immediate importance. This includes the screening effect of the well known zoologeal surface mat and synergistic or antagonistic effects on the organism of

interest caused by natural mixed populations of bacteria. Since our study was solely for isolating the importance of the adsorption phenomenon, these other factors were not explored.

In summary our study of bacterial adsorption thermodynamics has shown: Bacteria can and will travel through granular porous media. The rate of travel is governed by the adsorption capacity, X_m, of the porous media, the equilibrium constant, α, for the adsorption reaction, and uptake kinetics (not discussed herein). An equilibrium model (Appendix I) can be used to estimate travel in lieu of kinetic information. Also we have shown thermodynamics to be useful in understanding and describing the bacterial adsorption reaction which provides the necessary confidence in developing predictive models. However, once this has been done (by our work), it is not recommended that other systems be defined thermodynamically (in terms of ΔH°, ΔS°, and ΔF°) as a matter of routine operation since this is both laborious and difficult in terms of pragmatic returns. Measurement of α and X_m for a single specified temperature is of value and necessary, however, for rational assessment of bacterial travel through porous media.

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APPENDIX A

THERMODYNAMICS REVIEW

This will serve as a review and reference for some common thermodynamic statements. The derivation of expressions from beginning definitions is useful in understanding points of deviation between conventional applications of thermodynamics and application to bacterial adsorption.

First, let us define the following terms:

F	free energy (calories or liter-atm)
$\bar{F}$	partial molar free energy (calories/mole)
H	enthalpy (calories)
S	entropy (calories/°K)
E	internal energy (calories)
T	temperature (°K)
P	pressure (atmospheres)
V	volume (liters)
q	heat added to system (+), or from (-) (calories)
w	work done by system (+) (calories)
o	superscript used to indicate standard state
R	gas constant (1.98 cal/mole/°K)
K	equilibrium constant for a chemical reaction
α	equilibrium constant for a sorption reaction

Now we proceed to show the relationships between the thermodynamic variables and the factors of temperature and pressure (or concentration).

Free energy

Free energy is a defined function which has broader application than entropy in examining equilibrium conditions. By definition:

$$F \equiv H - TS \quad \ldots\ldots \quad (A\text{-}1)$$

At equilibrium:

$$dF = 0 \quad \ldots\ldots \quad (A\text{-}2)$$

[For purposes of this report we must define stability; in a thermodynamic sense a system is stable when no process can occur with a diminution in free energy.]

Free energy is the driving force in a process. Another useful term is partial molar free energy, $\bar{F}$, which is an intensive variable. No system can be in equilibrium unless the partial molar free energy of each substance involved is the same in every part of the system. If a substance is free to move, then it will move spontaneously to the state of lower chemical potential. Thus for phase equilibrium:

$$\bar{F}_A^{\alpha} = \bar{F}_A^{\beta} \quad \ldots\ldots \quad (A\text{-}3)$$

and

$$dF < 0 \quad \text{for any irreversible process} \quad \ldots \quad (A\text{-}4)$$

We can obtain a useful differential form of the free energy expression as follows:

$$F \equiv H - TS \quad \ldots\ldots \quad (A\text{-}1)$$

$$dF = dH - TdS - SdT \quad \ldots \quad (A\text{-}5)$$

$$= \{dE + PdV + VdP\} - TdS - SdT \quad (A\text{-}6)$$

$$= \{[dq - dw] + PdV + VdP\} - TdS - SdT \quad (A\text{-}7)$$

$$= \{[TdS - PdV] + PdV + VdP\} - TdS - SdT \quad (A\text{-}8)$$

- for a reversible process and PV work

$$= VdP - SdT \quad \ldots\ldots \quad (A\text{-}9)$$

This is one of the most useful basic equations.

Chemical equilibrium

Application of Equation (A-10) to problems of chemical equilibria is accomplished as follows:

At const. temp. $dF = VdP - S\overset{0}{dT}$ . . (A-10)

$$= nRT \frac{dP}{P} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}11)$$

$$F_2 - F_1 = nRT \ln P_2/P_1 \quad . \quad . \quad (A\text{-}12)$$

But define the initial state as the standard state.[1]

Then $F_1 = F^o$ and necessarily $P^o = 1$ atm at T

$$F_2 = F^o = nRT(\ln P_2 - \ln P^o) \quad . (A\text{-}13)$$

$$\text{or:} \quad F = F^o + nRT \ln P \quad . \quad . \quad (A\text{-}14)$$

which is another general equation having broad application.

Example. Application to equilibrium constant. For reaction, a moles of A goes to b moles of B:

$$aA_{(g)} \rightarrow bB_{(g)} \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}15)$$

$$F_A = F_A^o + aRT \ln P_A \quad . \quad . \quad . \quad (A\text{-}16)$$

$$F_B = F_B^o + bRT \ln P_B \quad . \quad . \quad . \quad (A\text{-}17)$$

$$\Delta F_{reaction} = F_B - F_A = F_B^o - F_A^o + bRT \ln P_B - aRT \ln P_A \quad . (A\text{-}18)$$

$$= \Delta F^o + RT \ln P_B^b/P_A^a \quad . \quad . \quad . \quad . (A\text{-}19)$$

in the special case where all reactants and products are in their standard states

$P_B^b = 1$, $P_A^a = 1$ and $\Delta F = \Delta F^o$

Suppose the reaction has proceeded to equilibrium, then:

$$0 = F^o + RT \ln P_{B\ equil}^b / P_{A\ equil}^a \quad . (A\text{-}20)$$

Reactants at their equilibrium pressure go to products at their equilibrium pressures, and thus $F = 0$

$$K_P = P_B^b/P_A^a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}21)$$

$$\therefore \Delta F^o = - RT \ln K_P \quad . \quad . \quad . \quad . (A\text{-}22)$$

Equation (A-22) states that when reactants in their standard states go to products in their standard states, there is a change in free energy equal to RT ln K_P.

We can generalize for the reaction:

$$aA + bB \rightarrow cC + dD \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}23)$$

$$\Delta F_{reaction} = \Delta F^o + RT \ln \frac{P_C^c P_D^d}{P_A^a P_B^b} \quad . (A\text{-}24)$$

Equation (A-24) can be generalized for any reaction by letting

Q = ratio of product pressures, or concentrations, each raised to its respective stoichiometric exponent, to reactant pressures, or concentrations, each raised to its respective stoichiometric exponent.

Thus in a more general sense

$$\Delta F_{reaction} = \Delta F^o + RT \ln Q \quad . \quad . \quad (A\text{-}25)$$

To express in terms of concentration (moles/liter), substitute

$$P_i = n_i(RT/V) = C_i RT \quad . \quad . \quad . \quad (A\text{-}26)$$

$$\therefore K_P = \frac{C_C^c C_D^d}{C_A^a C_B^b} \underbrace{(RT)^{c + d - a - b}}_{\text{stoichiometric const. - moles/liter}} \quad . \quad . \quad (A\text{-}27)$$

[1] The "standard state" is a reference state for the thermodynamic variables, F, H, and S and is taken arbitrarily at 1 atm, and 298°K. The standard enthalpy of any compound is the heat of the reaction by which it is formed from its elements, reactants and products all being in the standard state at 25°C and 1 atm. A zero value of free energy is assigned to the stable form of the elements at 25°C and 1 atm, also the hydrogen ion at unit activity is assigned a standard free energy of zero. The standard free energy of a compound (F_{298}^o) is the free energy of formation of that compound from its elements, considering reactants and products all to be in the standard state (25C and 1 atm).

$$= K_C(RT)^{\Delta n} \quad \ldots\ldots \text{(A-28)}$$

where Δn is the number of moles of products less that of reactants in the stoichiometric equation for the reaction. It makes little difference that these equations up through (A-28) have been developed using example reactions in the gas state. Substances in liquid solutions are treated in an identical manner; the relationships between gas and liquid states are Raoult's law and Henry's law.

Example. Inducing a reaction with an unfavorable equilibrium constant (i.e. $\Delta F^\circ < 0$).

Consider the hypothetical reaction at 27 C:

$$A \rightarrow B, \text{ where } K_P = \frac{P_B}{P_A} = 0.1$$

(a) Calculate ΔF° when A at 1 atm is converted to B at 1 atm.

$$\Delta F^\circ = - RT\ln K_P = - (1.99)(300)\ 2.303$$

$$\log 0.1 = + 1373 \text{ cal}$$

Thus it is clear since $\Delta F^\circ > 0$, that A at 1 atm, will not react spontaneously to give B at 1 atm. However, the reaction can be driven to the right by removing B as it is formed or increasing the partial pressure of A.

(b) Calculate ΔF at 27C for the production of 1 mole of B at a pressure of 1 atm from A at a pressure of 20 atm.

$$A(p = 20) \rightarrow B(p = 1)$$

$$\Delta F = -RT \ln K_P + RT \ln \frac{P_B}{P_A}$$

$$= \Delta F^\circ + (1.99)(300)(2.303) \log 1/20$$

$$= 1373 - 1786 = - 413 \text{ cal}$$

Thus under these conditions the reaction can proceed spontaneously.

van't Hoff's relationship

To derive the expression relating the equilibrium constant, enthalpy, and temperature we proceed as follows, deriving also the Gibbs-Helmholtz equation during the process.

1. Start with equilibrium relationship:

$$\Delta F^\circ = - RT \ln K. \quad \ldots\ldots \text{(A-29)}$$

2. Differentiate with respect to temperature:

$$- \frac{d(\Delta F^\circ)}{dT} = R \ln K + RT \frac{d \ln K}{dT} \quad \ldots \text{(A-30)}$$

3. Now recall $dF = VdP - SdT \quad \ldots\ldots \text{(A-10)}$

Differentiate with respect to T:

$$\left(\frac{\partial F}{\partial T}\right)_P = - S \quad \ldots\ldots \text{(A-31)}$$

Subtracting state 1 from state 2 condition gives:

$$-\Delta S = -(S_2 - S_1) = \left(\frac{\partial F_2}{\partial T}\right)_P - \left(\frac{\partial F_1}{\partial T}\right)_P \quad \ldots\ldots \text{(A-32)}$$

$$\left[\frac{\partial(\Delta F)}{\partial T}\right]_P \quad \ldots\ldots \text{(A-33)}$$

Now recall that for an isothermal process:

$$\Delta F = \Delta H - T\Delta S \quad \ldots \text{(A-34)}$$

Substituting for ΔS yields:

$$\Delta F = \Delta H + T \left[\frac{\partial(\Delta F)}{\partial T}\right]_P \quad \ldots \text{(A-35)}$$

which is the Gibbs-Helmholtz equation.

4. Substitute Equation (A-23) in Gibbs-Helmholtz, using G-H equation in standard state:

$$\Delta H^\circ - \Delta F^\circ = RT\ln K + RT^2 \frac{d\ln K}{dT} \quad \ldots \text{(A-36)}$$

5. Since $\Delta F^{\circ} = - RT \ln K$, Equation (A-29), Equation A-36) becomes:

$$\frac{d \ln K}{dT} = \frac{\Delta H^{\circ}}{RT^2} \quad \ldots\ldots\ldots \text{(A-37)}$$

6. If we assume ΔH° is constant, then we have van't Hoff's relation:

$$\ln K = - \Delta H^{\circ}/RT + C \quad \ldots\ldots \text{(A-38)}$$

A graphical expression of Equation (A-30) is the clearest means for its interpretation; thus we plot log K vs. 1/T. A negative slope means ΔH° is positive, which means the reaction (say $aA \rightarrow bB$, ΔH° (+)) is endothermic (absorbs heat). Also from Equation (A-30) we see mathematically that $K << 1$, hence the reaction is not spontaneous in the direction indicated.

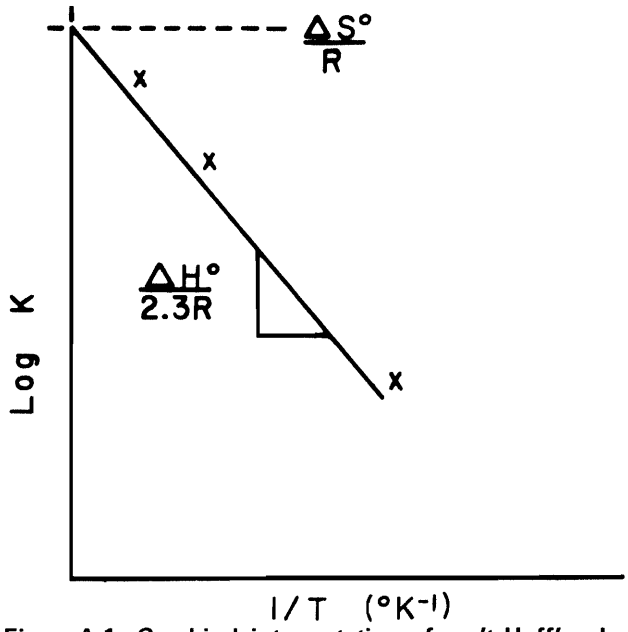


Figure A-1. Graphical interpretation of van't Hoff's relation.

APPENDIX B

BACTERIAL ADSORPTION DATA PROCESSING PROGRAMS

Two programs, BACTXT and ALPHAB, were written to process the bacterial depletion data and the equilibrium data, respectively. These programs are described below.

BACTXT

Figure B-1 is the deck setup for running the BACTXT program. Figure B-2 is a program listing of BACTXT in Fortran V, as run on the Univac 1108. Following the program listing are the code sheets of input data (Figures B-3, B-4) and an output list of these same data.

This program averages two plate counts (if two valid observations are indicated, otherwise only one is used), calculates the dilution factor based upon the number of serial transfers used in plating, calculates the concentration, C, of bacteria remaining in solution at each observation time, and the corresponding uptake by adsorption to the solid phase, $\overline{X}$.

Output is in both tabular and graphical form. The tabular output, shown in Figure B-6, reproduces all recorded data on the coding sheets (Figures B-3 and B-4) as well as the corresponding $\overline{X}$ and C values. The program has the option of using either the PRTPLT subroutine or the GERBER plotter for graphical output. Output from PRTPLT is shown as Figures B-7 and B-8 for $\overline{X}$ vs. t and C vs. t respectively. Figure B-9 combines the same data into a single output using the GERBER plotter portion of the BACTXT program (the curves shown were done by hand).

ALPHAB

Figure B-10 is the deck setup for ALPHAB input data. Figure B-11 is the program listing of ALPHAB in Fortran V, for the Univac 1108. Following the program listing is a sample of the coding sheet (Figure B-12) containing equilibrium data, C^* and $\overline{X}^*$ from the array of experimental runs at a given temperature. Figure B-13 is a listing of these data after punching on cards in the format specified by ALPHAB.

This program first calculates the data in linearized form in accordance with Equation (12). It then does a regression analysis by subroutine REGLOG using $C^*/\overline{X}^*$ vs. C^* as arguments. The best fit slope and intercepts are then fed back to the main program which uses these values to calculate X_m and α; the subroutine REGLOG also returns values of R and R^2.

Output is again both tabular and graphical. Figure B-14 is a sample. Not only are calculated values shown but experimental conditions and equilibrium data are reproduced. The GERBER plotter portion of the program produces two graphical outputs—a linearized Langmuir isotherm, Figure B-15, and a conventional Langmuir isotherm, Figure B-16. Both plotted points and the best fit curves are drawn in each case.

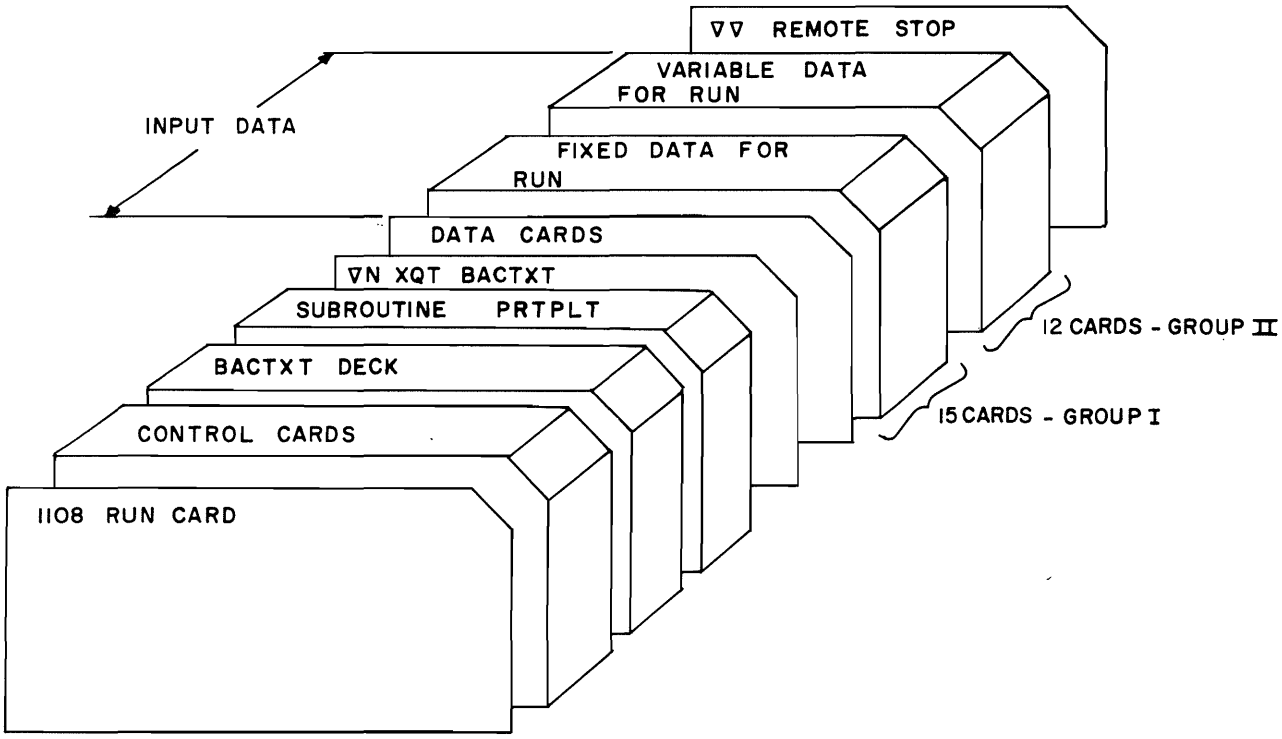


Figure B-1. Deck set-up for BACTXT data input.

```
C     PROJECT WG-62 BACTERIAL ADSORPTION ON SOILS
C     IF RUN IS 'CONTROL', ODWT = 100
C     VTZERO IS VOL PRIOR TO ADDITION OF SORBENT, C(I) MUST BE ADJUSTED
C     TO SOLVOL BY FACTOR VTZERO/SOLVOL
C     CALCULATION OF XBAR VS TIME FROM RAW DATA
      DIMENSION  TSUM(20),DILNO(20),PIPVOL(20),          VALOBS(20),
     2AVGPC(20),DILFCT(20),C(20),XBAR(20),PLACNT(20,10)
      DIMENSION DATE(2),TYPE(2),SBATE(3),STRAIN(2),SBENT(3),SKIND(3)
      INTEGER HOUR,RUN
      READ(5,895)NXTBAR
  895 FORMAT(I5)
    1 READ(5,15)DATE,HOUR
   15 FORMAT(2A6  /I12)
      IF(HOUR .GT.2400) GO TO 99
      READ(5,15)            RUN,TYPE,SBATE,STRAIN,SBENT,SKIND,APPCON,SAMV
     2OL,SOLVOL,ODWT,N,TEMP,VTZERO,(TSUM(I),DILNO(I),PIPVOL(I),PLACNT
     3(I,1),VALOBS(I),PLACNT(I,2),I=1,N)
   15 FORMAT ( I8/2A4/3A6    /2A6     /3A6/3A6/F12.0/F5.1/F10.1/F5.1/I8/F6
     2.1/F6.1/(5F12.3/3FX,F12.3))
      VOLREM = SOLVOL
      TSBARE = 0.
      DO 25 I =1,N
      VOLREM = VOLREM - SAMVOL
      VOLRM = VOLREM
      AVGPC(I) =  (PLACNT(I,1) + PLACNT(I,2))/VALOBS(I)
      DILFCT(I) = (10.**(2.*DILNO(I)))/PIPVOL(I)
      C(I) = AVGPC(I)*DILFCT(I)
      TSBATR = TSBARE + SAMVOL*C(I)
      TSBARE = TSBATR
      CITM1 = AVGPC(1)*DILFCT(1)
      C(1) = CITM1*VTZERO/SOLVOL
      IF(ODWT .GT. 50.) GO TO 23
      XBAR(I) = (C(1)*SOLVOL - C(I)*VOLREM - TSBATR )/ODWT
      GO TO 25
   23 XBAR(1) = 0.
   25 CONTINUE
      XBAR(1) = 0.
      WRITE(6,100) DATE,SBATE,SOLVOL,HOUR,STRAIN,ODWT,RUN,SBENT,TYPE,SKI
     2ND,APPCON,TEMP,SAMVOL
  100 FORMAT(1H1/27X'TABLE 2  BACTERIAL ADSORPTION EXPERIMENTS - COLLECT
     2ION AND REDUCTION OF DATA'//20X'DATE',2X,2A6,12X'SORBATE',2X,2A6,1
     33X'SOL. VOL.',F10.1,2X'ML'/20X'HOUR',I7,1X'HRS',24X,2A6,10X'SORBEN
     4T WT. (OD)',F5.1,2X'GM'/20X'RUN',I7,20X'SORBENT',3A6/20X'TYPE OF R
     5UN',2X,2A4,14X,3A6/50X,'INITIAL CONC (SPECT READ)',F10.1,2X'BUGS/M
     6L'/50X'TEMP',F5.1,2X'DEG. C.'/50X'SAMPLE VOL.',F5.1,2X'ML'///)
      WRITE(6,102)
  102 FORMAT ( 5X'ELAPSED',3X'NO. OF DIL.',5X'PIPET VOL.',5X'FILTER',7X'
     2NO. OF',6X'AVG FILTER',5X'DIL. FACT.',4X'SOLUTION',7X'XBAR'/ 5X'TI
     3ME',5X'OF 90 ML EA.',3X'DEL. TO PLATE',3X'PLATE COUNT',7X'VALID OB
     4S.',3X'PLATE COUNT',21X'CONC.'/ 5X'(MIN)',22X'(ML)',9X'(BUGS/PLATE
     5)',15X'(BUGS/PLATE)',18X'(BUGS/ML)',4X'(BUGS/GM)'/)
      WRITE(6,101) (TSUM(I),DILNO(I),PIPVOL(I),PLACNT(I,1),VALOBS(I),AVG
     2PC(I),DILFCT(I),C(I),XBAR(I),PLACNT(I,2),I=1,N)
  101 FORMAT (   F11.1,4X,F7.0,4X,F12.1,4X,F12.0,F11.0,4X,F12.0,4X,F10.0
     2,1X,F13.0,F14.0/42X,F12.0/)
      IF(NXTBAR .EQ. 1)GO TO 895

C     BEGIN OPERATION OF PLOTTER TO PLOT XBAR VS TSUM
C     STEP 1 ESTABLISH DIMENSIONS OF PLOT PAPER
      LN = N-1
      EQUILX = (XBAR(1) + XBAR(LN))/2.
      EQUILC = (C(1) + C(LN))/2.
      CALL JOPLOT (14.0,10.0)
C     STEP 2 PROVIDE MAILING INSTRUCTIONS
      CALL SYMBL4(0.2,0.0,0.10,34HMAIL TO D. W. HENDRICKS, DWRL, UTAH
     2STATE UNIV., LOGAN, UTAH 84321  SEND BY FIRST CLASS MAIL,60.0,68)
C     STEP 3 ESTABLISH PERMANENT ORGIN FOR GRAPH
      CALL PLOT(1.5,7.0,-3)
C     STEP 4 ESTABLISH X-AXIS, THEN Y-AXIS - LABEL EACH
      ALX = 12.0
      ALY = 9.
      CALL SCALE (TSUM, N,ALX,TMIN,DTIME,1)
      CALL AXIS (0.0, 0.0, 10HTIME (MIN),-10,ALX,0.0,TMIN, DTIME)
      CALL SCALE (XBAR, N, ALY, XBARMN, DXBAR,1)
      CALL AXIS (0.0, 0.0, 27HXBAR  (BACTERIA/CM SQUARE), 27, ALY,
     290.0, XBARMN, DXBAR)
C     STEP 7 SHOW THE EXP POINTS
      CALL PLOT (0.0, 0.0, 3)
      DO 401 I = 1,N
  401 CALL SYMBL4(TSUM(I), XBAR(I), 0.14, 1HX, 0.0, 1)
C     STEP 8 LABEL GRAPH
      CALL SYMBL4 (7.0,-1.0, 0.20, 20HBACTERIAL ADSORPTION, 0.0, 20)
      CALL SYMBL4 (7.6,-1.25,0.10, 4HDATE, 0.0,4)
      CALL SYMBL4 (8.0,-1.25,0.10, DATE, 0.0, 12)
      CALL SYMBL4 (7.6,-1.5, 0.10, 5HRUN,0.0, 3)
      CALL NUMBRI (7.6,-1.5, 0.10, RUN, 0.0)
      CALL SYMBL4 ( 7.6,-1.5, 0.10, 4HTEMP, 0.0, 4)
      CALL NUMBRF ( 7.6,-1.5, 0.10, TEMP, 0.0,5)
      CALL SYMBL4 (8.3,-1.5, 0.10, 7HSORBENT,0.0, 7 )
      CALL SYMBL4 (10.1,-1.5,0.10, SBENT, 0.0, 18)
      CALL SYMBL4 (8.3,-1.75,0.10, 7HSORBATE, 0.0, 7 )
      CALL SYMBL4(10.1,-1.75,.10, SBATE, 0.0,18)
      CALL SYMBL4 (8.3,-1.5),0.10,6HSTRAIN, 0.0,6)
      CALL SYMBL4 (10.1,-1.5,0.10,STRAIN, 0.0, 12)
C     STEP 9 DO C(I) CURVE
      CALL SCALE (C,N,ALY,CMIN,CCONC,1)
      CALL AXIS (12.0,0.0,37HSOLUTION CONCENTRATION  (BACTERIA/ML),-37,
     2ALY, 90.0,CMIN, CCONC)
C     GO BACK TO ORIGIN WITH PEN UP
      CALL PLOT (0.0,0.0,3)
C     SHOW EXPERIMENTAL POINTS FOR CONC
      DO 405 I = 1,N
  405 CALL SYMBL4 (TSUM(I), C(I), 0.14, 1HO, 0.0,1)
      CALL PLOT (-1.0,-1.0,-3)
      CALL FINI
  99  CONTINUE
      DATA YAXIS,XAXIS/4HXBAR,3HMINUTE/
      SCXXES.0
      XMINES.
      PER.
      YZERO.E+00
      IC=24
      CALL PRTPLT(SCXX,N,TSUM,XMIN,XBAR,P,YZ,YAXIS,XAXIS,IC)
      DATA ZAXIS,XAXIS/5HCONC. ,6HMINUTE/
      YZERO.E+06
      CALL PRTPLT(SCXX,N,TSUM,XMIN,C,   P,YZ,ZAXIS,XAXIS,IC)
      GO TO 1
   99 STOP
      END
```

Figure B-2. Program listing of BACTXT.

```
      SUBROUTINE PRTPLT(SCXX,N,NY,NMP,LP,X,XMIN,Y,P,YZ,YAXIS,XAXIS,IC)
C     SUBROUTINE PRTPLT FOR PLOTTING X,Y POINTS ON GRAPH.X SCALE MUST BE
C        KNOWN. Y SCALE MAX VALUE WILL BE READ AND ADJUSTED IF NOT KNOWN.
C     IF YMAX .LT. 2 TIMES INTERVAL SET, INTERVAL READJUSTED TO FIT
C     FIGURE LIMITS.
C     ARGUMENTS AS FOLLOWS
C       SCXX=SCALE FACTOR FOR X AXIS UNITS PER INCH WITH 12 INCHES
C       N=NUMBER OF X AND Y OBSERVATIONS. FROM MAIN PROGRAM
C        X=X ARRAY FROM MAIN PROGRAM-LIMIT ONE
C       XMIN=NMIN = VALUE OF X ORIGIN
C        Y=Y ARRAY FROM MAIN PROGRAM-MAYBE MORE THAN ONE.
C       P=YMIN(1)=ORIGIN OF Y AXIS. ONE YMIN(J) FOR EACH Y ARRAY
C       YZ=NYL(1)=INCREMENT OF Y AXIS. 9 INCHES
C       YAXIS= LABEL FOR Y AXIS. APPEARS TOP LEFT  LINE OF FIGURE ( A6)
C       XAXIS= LABEL FOR X AXIS  APPEARS TOP CENTER OF FIGURE ( A6)
C       IC=M(J)=INTEGER SPECIFYING MODE OF X AND Y FOR PRINTING FORMATS
C                14 X=E FIELD, Y=E FIELD
C                15 X=E FIELD, Y=F FIELD
C                24 X=F FIELD, Y=F FIELD
C                25 X=F FIELD, Y=F FIELD
C     ARGUMENTS FIXED FOR THIS SUBROUTINE BUT WHICH CAN BE VARIED TO
C     PUT MULTIPLE Y'S ON SAME FIGURE (NO SCALES PRINTED) AND TO LIST
C     TRANSFORMED X AND Y'S  ARE AS FOLLOWS
C       JTEST= 0 NO X TRANSFORM, =1 LOG10
C       ITEST(J) = 0 NO Y TRANSFORM.   =1,LOG10.ONE ITEST FOR EACH Y
C          ARRAY
C       NY=NUMBER OF SEPARATE Y ARRAYS =1 NORMALLY
C       PT(J) = PLOT SYMBOL FOR EACH XY POINT. ONE FOR EACH Y ARRAY
C       NMP=SINGLE=0 OR MULTIPLE=1 PLOTS ON SAME FIGURE. NO YSCALE IF 1
C       LP=LIST OPTION.0=NO LIST,1=TABLE GENERATED
      REAL NX,NMIN,NYL,ND
      DIMENSION NX(300),Y(300,10),A(125,60),A0(300,10),        ND(12),
     1B(60),IIX(300),IIY(300,10),ITEST(10),          PT(10),YMIN(10),
     2NMIS(10),NYL(10),YS(10),X(300),                    M(10)
      DATA BLANK,ZERO,DASH,TICK,ORIG,PT(1)/1H ,1H0,1H-,1HI,6HORIGIN,1H+/
      DO 802 I=1,N
      NX(I)=X(I)
  802 CONTINUE
      NYL(1)=YZ
      YMIN(1)=P
      NMIN=XMIN
      JTEST=0
      NY=1
      ITEST(1)=0
      NMP=0
      M(1)=IC
      LP=0
      Z=1.
C     ESTABLISH BOUNDRY MARKS
      DO 5 I=1,121
      DO 5 J=1, 60
      B(J)=BLANK
    5 A(I,J)=BLANK
      DO 35 J=1,55
   35 A(2,J)=TICK
      DO 65 J=1,55,5
   65 A(1,J)=DASH
      DO 31 I=3,121
      A(I,1)=DASH
   31 A(I,55)=DASH
      DO 52 I=2,121,10
   52 A(I,56)=TICK
C     SCALE X AND TRANSFORM X OR NOT
      SCLX=10./SCXX
      IF(JTEST.EQ.0) GO TO 2
      DO 3 I=1,N
      IF(NX(I).GT.10.E+19) GO TO 3
      IF(NX(I).LE.0.) GO TO 3
      NX(I)=ALOG10(NX(I))
    3 CONTINUE
    2 DO 22 I=1,N
      IIX(I)=SCLX*(NX(I)-NMIN)+2.5
      IF(IIX(I).GT.121)IIX(I)=121
      IF(IIX(I).LT.2)IIX(I)=2
   22 CONTINUE
C     DETERMINE MISSING VALUES OF Y ONLY. X MUST BE COMPLETE
      DO 4 J=1,NY
    4 NMIS(J)=0.
      ND(1)=NMIN
      DO 41 I=2,12
   41 ND(I)=ND(I-1)+SCXX
C     BEGIN Y DETERMINATION AND PLOT-PRINT-POINT-VALUES
      DO 70 J=1,NY
C     SEARCH FOR MISSING DATA AND TRANSFORM Y IF CALLED FOR
      DO 500 I=1,N
      Z=SIGN(Z,Y(I,J))
      IF(Z)13,500,500
   13 NMIS(J)=NMIS(J)+1
      Y(I,J)=10.E+20
      GO TO 500
  500 CONTINUE
      IF(ITEST(J).EQ.0)GO TO 78
      DO 77 I=1,N
      IF(Y(I,J).GT.10.E+19) GO TO 77
      IF(Y(I,J).LE.0.)GO TO 77
      Y(I,J)=ALOG10(Y(I,J))
   77 CONTINUE
C     SCALE Y
   78 K=1
   87 IF(Y(K,J).LT.10.E+19) GO TO 79
      K=K+1
      IF(K.LE.N) GO TO 87
   79 YMAX=Y(K,J)
      K=K+1
      DO 10 I=K,N
      IF(Y(I,J).GT.10.E+19) GO TO 10
      IF(Y(I,J).GT.YMAX)YMAX=Y(I,J)
   10 CONTINUE
      C=NYL(J)
C     CHANGES Y SCALE TO FIT DATA
      S=(YMAX-YMIN(J))/9
      IF(S.GT.C) GO TO 602
```

Figure B-2. Continued.

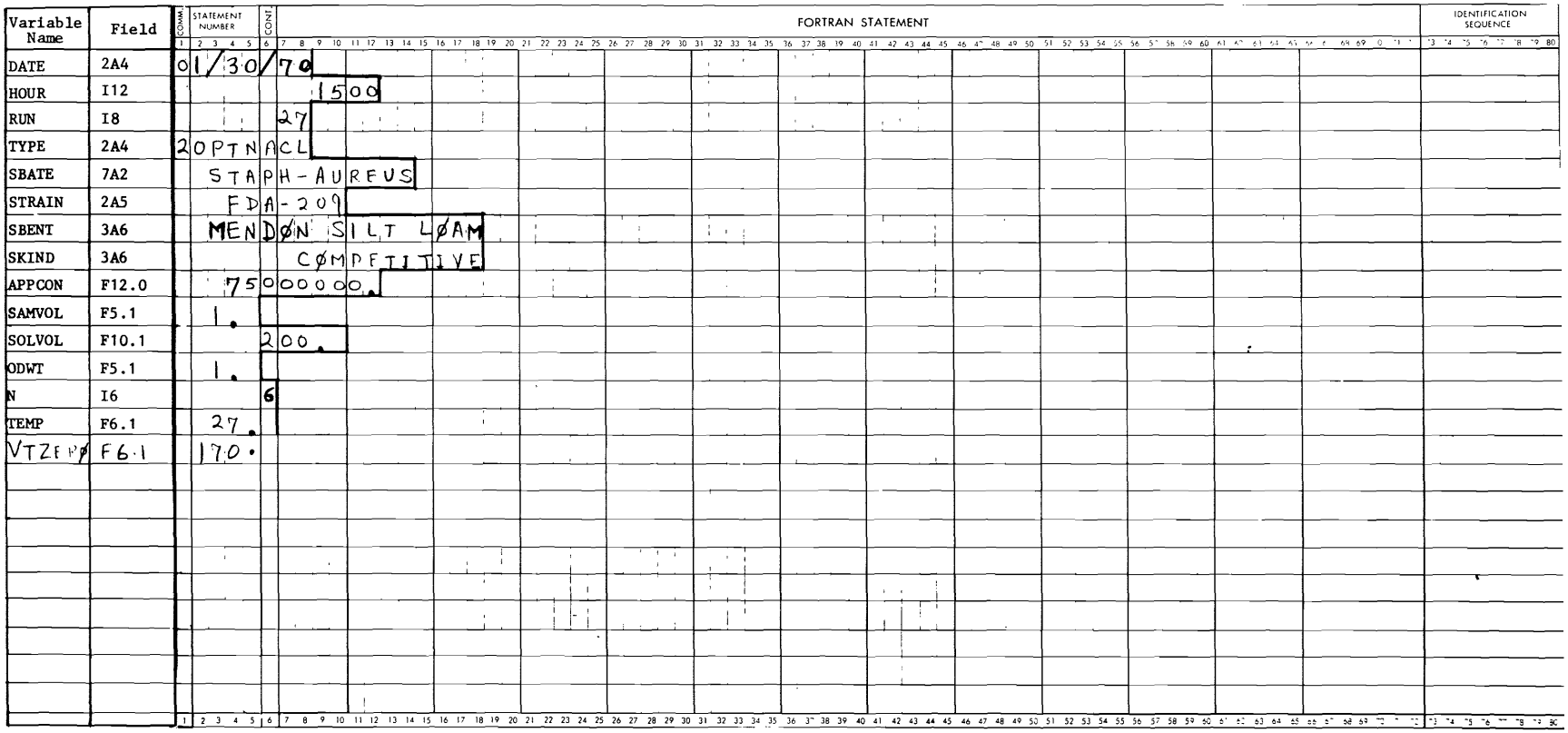
```
      IF(S.LT.C*.22222222) GO TO 607
      GO TO 96
C     REDUCES Y SCALE AND SETS NEW INTERVAL C IF YMAX TOO LOW ON SCALE
  607 DO 661I=10,10000,10
      R=C/I
      IF(S.GT.R*.22222222.AND.S.LT.R) GO TO 604
C     IF SCALE REDUCED TOO FAR, EXPAND AGAIN
      IF(S.GT.R) GO TO 605
   66 CONTINUE
  605 CER
C      INCREASES SCALE AND SETS NEW INTERVAL C
  602 DO 99 I=2,100
      R=I*C
      IF(S.LE.R) GO TO 604
   99 CONTINUE
  604 CER
   96 SCLY=E.0/C
      IF(NMP.NE.0)GO TO 21
      B(1)=YMIN(J)
      DO 20 JI=7,55,5
   20 B(JI)=B(JI-5)+C
      YS(J)=C
   21 DO 15 I=1,N
      IF(Y(I,J).GT.10.E+19) GO TO 11
      IIY(I,J)=SCLY*(Y(I,J)-YMIN(J))+1.5
      IF(IIY(I,J).GT.55)IIY(I,J)=55
      IF(IIY(I,J).LT.1)IIY(I,J)=1
      IX=IIX(I)
      IY=IIY(I,J)
      IF(IX.EQ.2) GO TO 61
      IF(IY.EQ.1.OR.IY.EQ.55) GO TO 62
   11 A0(I,J)=BLANK
      GO TO 14
   61 A0(I,J)=TICK
      GO TO 14
   62 A0(I,J)=DASH
   14 IF(Y(I,J).GT.10.E+19) GO TO 15
      A(IX,IY)=PT(J)
   15 CONTINUE
      IF(NMP.NE.0)GO TO 63
C
C     PLOT FIGURE X VS. ONE Y
C
      WRITE(6,102)YAXIS,YS(J),XAXIS,N
  102 FORMAT(1H1,A6,1X,E10.3,' UNITS/INCH.',22X,A5,18X,'NOBS =',I5)
      DO 85 L=1,55
NOSTIC.  THE TEST FOR EQUALITY BETWEEN NON-INTEGERS MAY NOT BE MEANINGFUL.
      IF(A(56-L).EQ.BLANK) GO TO 81
      IF(M(J).EQ.15.OR.M(J).EQ.25) GO TO 42
   80 WRITE(6,103)(56-L),(A(I,56-L),I=1,121)                              YEF
      GO TO 85
   42 WRITE(6,110)B(56-L),(A(I,56-L),I=1,121)                             YEF
      GO TO 85
   81 WRITE(6,104)(A(I,56-L),I=1,121)                                     YE
   85 CONTINUE
  103 FORMAT(1X,E8.4,121(A1))                                             YEF
  110 FORMAT(1X,F8.3,121(A1))
      WRITE(6,104)(A(I,56),I=1,121)                                       YE
  104 FORMAT(9X,121A1)                                                    YE
      IF(M(J).EQ.24.OR.M(J).EQ.25) GO TO 43
      WRITE(6,107)(NP(I),I=1,12)                                                XEF
      GO TO 64
   43 WRITE(6,104)(NP(I),I=1,12)                                                XEF
  106 FORMAT(1H ,6X,12(F7.3,3X))                                                XE
  108 FORMAT(1H ,6X,12(F6.1,4X))                                                XE
   64 DO 67 I=1,N
      IX=IIX(I)
      IY=IIY(I,J)
   67 A(IX,IY)=A0(I,J)
      IF(IP.EQ.0)GO TO 70
      IF(J.EQ.NY)GO TO 69
      GO TO 73
   69 IF(J.NE.NY)GO TO 70
C
C     PRINT TRANSFORMED DATA IN TABLE
C
   73 WRITE(6,131)SCXX,N
  131 FORMAT(1H1,'MULTIPLE PLOT DATA',2X'Y AXIS ONE INCH =',E5.1,'.',8X,
     2' NOBS =',I5)
   50 WRITE(6,117)(PT(K),K=1,NY)
  117 FORMAT(11H PLOT CHAR 10X4(1X,9(1PXA)))
      WRITE(6,120)(PT(K),YMIN(K),K=1,NY)                                    Y=F
  120 FORMAT(1X,A6,'=',1PE13.3,10E13.3)
      WRITE(6,120)(YS(K),K=1,NY)
  120 FORMAT(11H UNIT/IN=1PE13.3,10E13.3)
      WRITE(6,121)(NMIS(K),K=1,NY)
  121 FORMAT('1',11H NO MISSING,6X,10I10)
  150 DO 86  I=1,N
   86 WRITE(6,123)NX(I),(Y(I,K),K=1,NY)                                    XEF YEF
  123 FORMAT(7X,F10.3,1PE10.3)
      IF(NMP.EQ.0)GO TO 70
C
C     PRINT FIGURE X VS. UP TO 10 Y'S BUT Y AXIS NOT LABELED
C
      WRITE(6,124)(PT(I),I=1,NY)
  124 FORMAT(1H1,'MULTIPLE  Y PLOT',13(8X,A2))
      DO 90 L=55,1,-1
   90 WRITE(6,104)(A(I,L),I=1,121)
      WRITE(6,104)(A(I,56),I=1,121)
      IF(M(J).EQ.24.OR.M(J).EQ.25) GO TO 177
      WRITE(6,107)(NP(I),I=1,12)                                                XEF
      GO TO 178
  177 WRITE(6,107)(NP(I),I=1,12)                                                XEF
  178 DO 91 I=1,N
      DO 91 K=NY,1,-1
      IX=IIX(I)
      IY=IIY(I,K)
   91 A(IX,IY)=A0(I,K)
   70 CONTINUE
      RETURN
      END

F COMPILATION:          1 DIAGNOSTICS.
```

Figure B-2. Continued.

BACTERIAL ADSORPTION EXPERIMENTS – COLLECTION OF DATA

(A) FIXED DATA FOR RUN



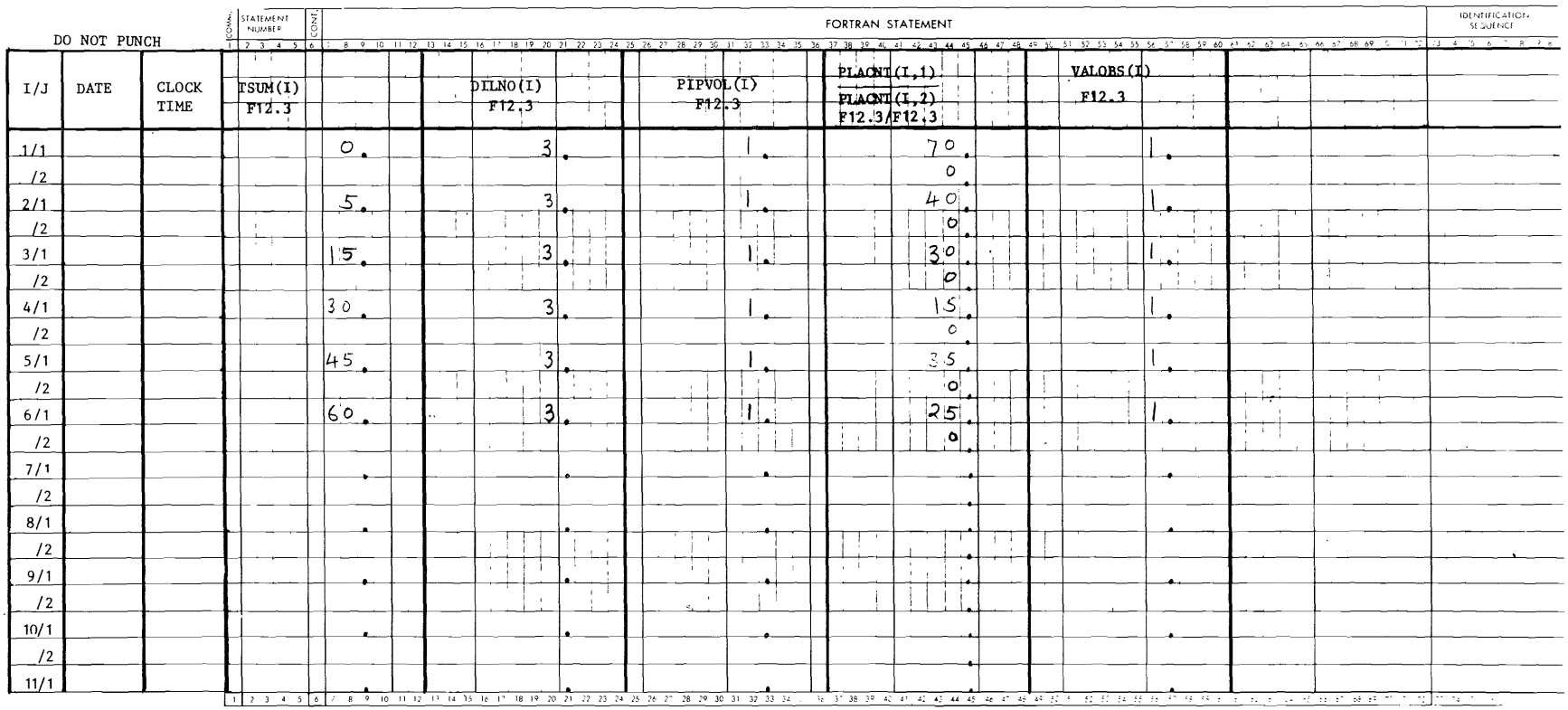
Variable Name	Field	Value
DATE	2A4	01/30/70
HOUR	I12	1500
RUN	I8	27
TYPE	2A4	20PTNACL
SBATE	7A2	STAPH-AUREUS
STRAIN	2A5	FDA-209
SBENT	3A6	MENDØN SILT LØAM
SKIND	3A6	CØMPETITIVE
APPCON	F12.0	75000000.
SAMVOL	F5.1	1.
SOLVOL	F10.1	200.
ODWT	F5.1	1.
N	I6	6
TEMP	F6.1	27.
VTZERØ	F6.1	170.

Initial Dave

Figure B-3. IBM coding sheet for recording fixed data for adsorption run.

BACTERIAL ADSORPTION EXPERIMENTS – COLLECTION OF DATA

(A) VARIABLE DATA FOR RUN



DO NOT PUNCH										
I/J	DATE	CLOCK TIME	TSUM(I) F12.3		DILNO(I) F12.3		PIPVOL(I) F12.3	PLACNT(I,1) / PLACNT(I,2) F12.3/F12.3	VALOBS(I) F12.3	
1/1				0.	3.		1.	70.		1.
/2								0.		
2/1				5.	3.		1.	40.		1.
/2								0.		
3/1				15.	3.		1.	30.		1.
/2								0.		
4/1				30.	3.		1.	15.		1.
/2								0.		
5/1				45.	3.		1.	35.		1.
/2								0.		
6/1				60.	3.		1.	25.		1.
/2								0.		
7/1										
/2										
8/1										
/2										
9/1										
/2										
10/1										
/2										
11/1										

Initial Dave

Figure B-4. IBM coding sheet for recording variable data for adsorption run.

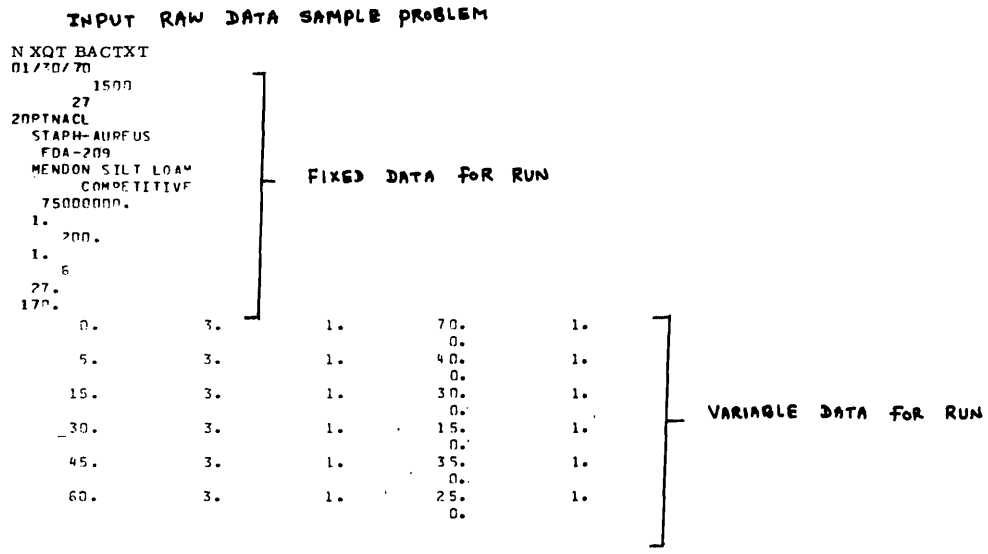


Figure B-5. Listing of fixed and variable data for adsorption run.

SAMLE OUTPUT FOR ABOVE DATA (TABLE)

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 01/30/70
HOUR 1500 HRS
RUN 27
TYPE OF RUN 20PTNACL

SORBATE STAPH-AUREUS
FDA-209
SORBENT MENDON SILT LOAM
COMPETITIVE
INITIAL CONC (SPECT READ) 75000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 200.0 ML
SORBENT WT. (DD) 1.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	70. 0.	1.	70.	1000000.	5950000000.	0.
5.0	3.	1.0	40. 0.	1.	40.	1000000.	4000000000.	3870000000.
15.0	3.	1.0	30. 0.	1.	30.	1000000.	3000000000.	3650000000.
30.0	3.	1.0	15. 0.	1.	15.	1000000.	1500000000.	3450000064.
45.0	3.	1.0	35. 0.	1.	35.	1000000.	3500000000.	3365000064.
60.0	3.	1.0	25. 0.	1.	25.	1000000.	2500000000.	3335000000.

Figure B-6. Output from BACTXT-tabular printout.

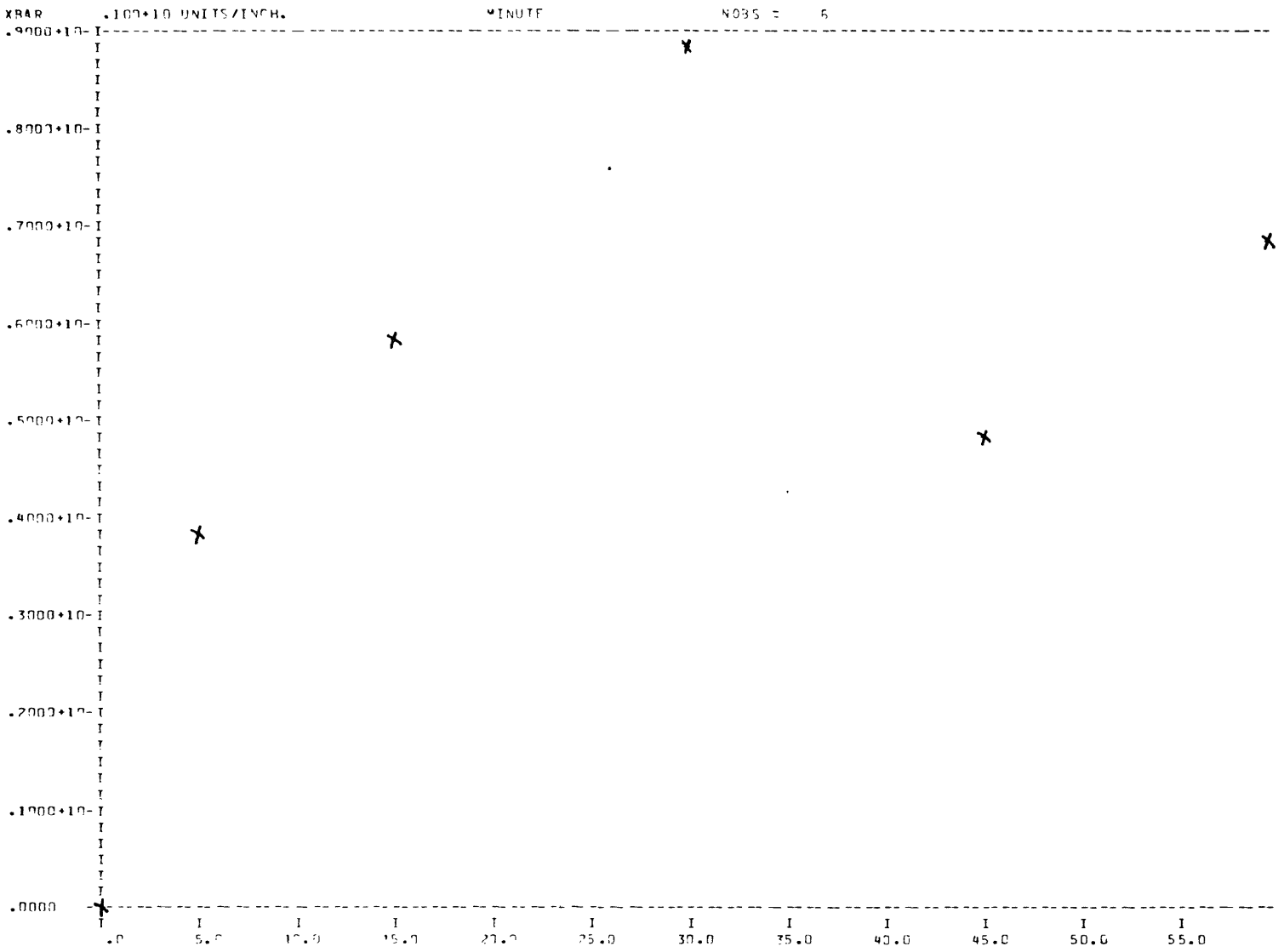


Figure B-7. Output from BACTXT-bacterial uptake curve by PRTPLT subroutine.

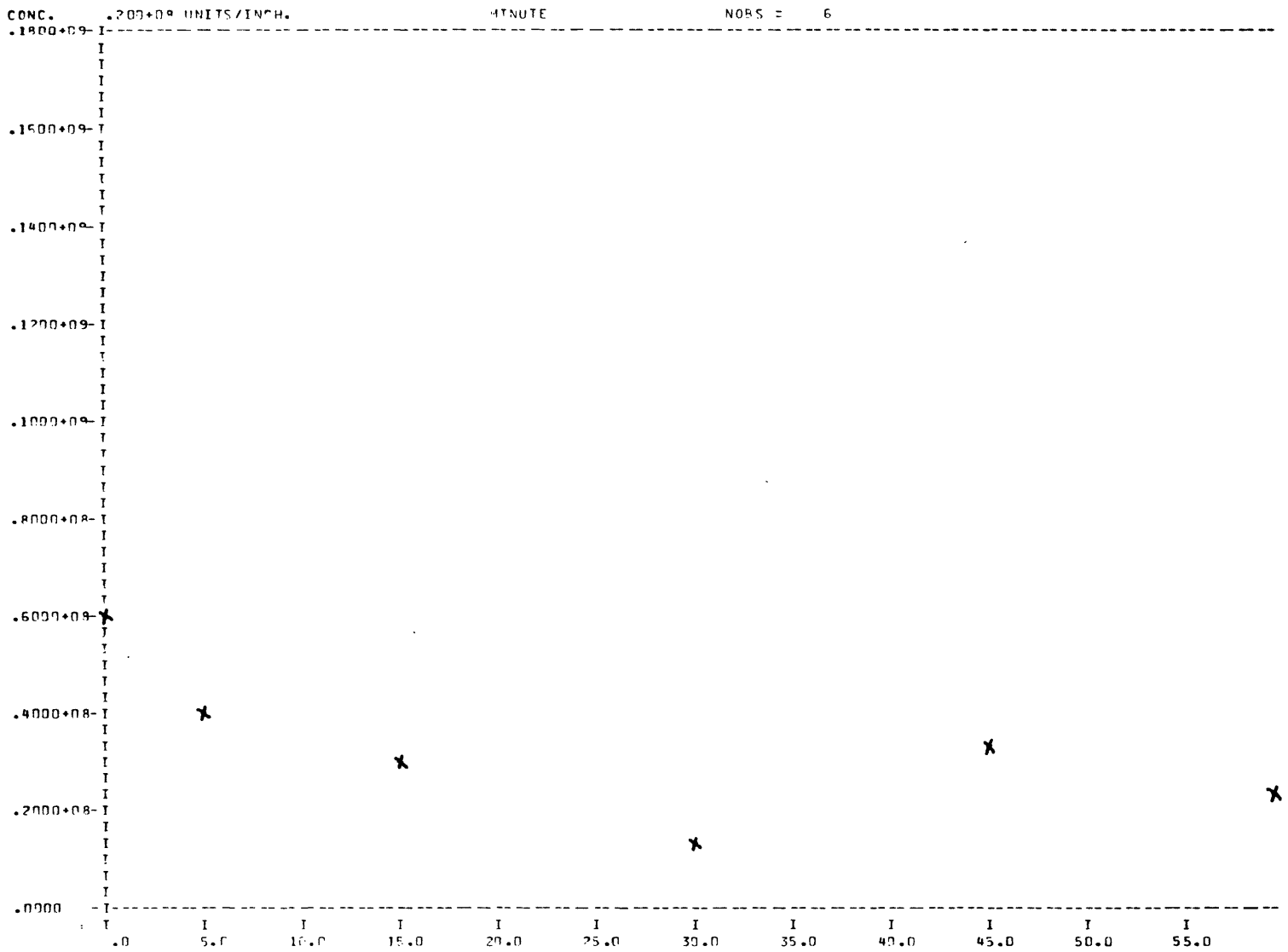


Figure B-8. Output from BACTXT-bacterial depletion curve by PRTPLT subroutine.

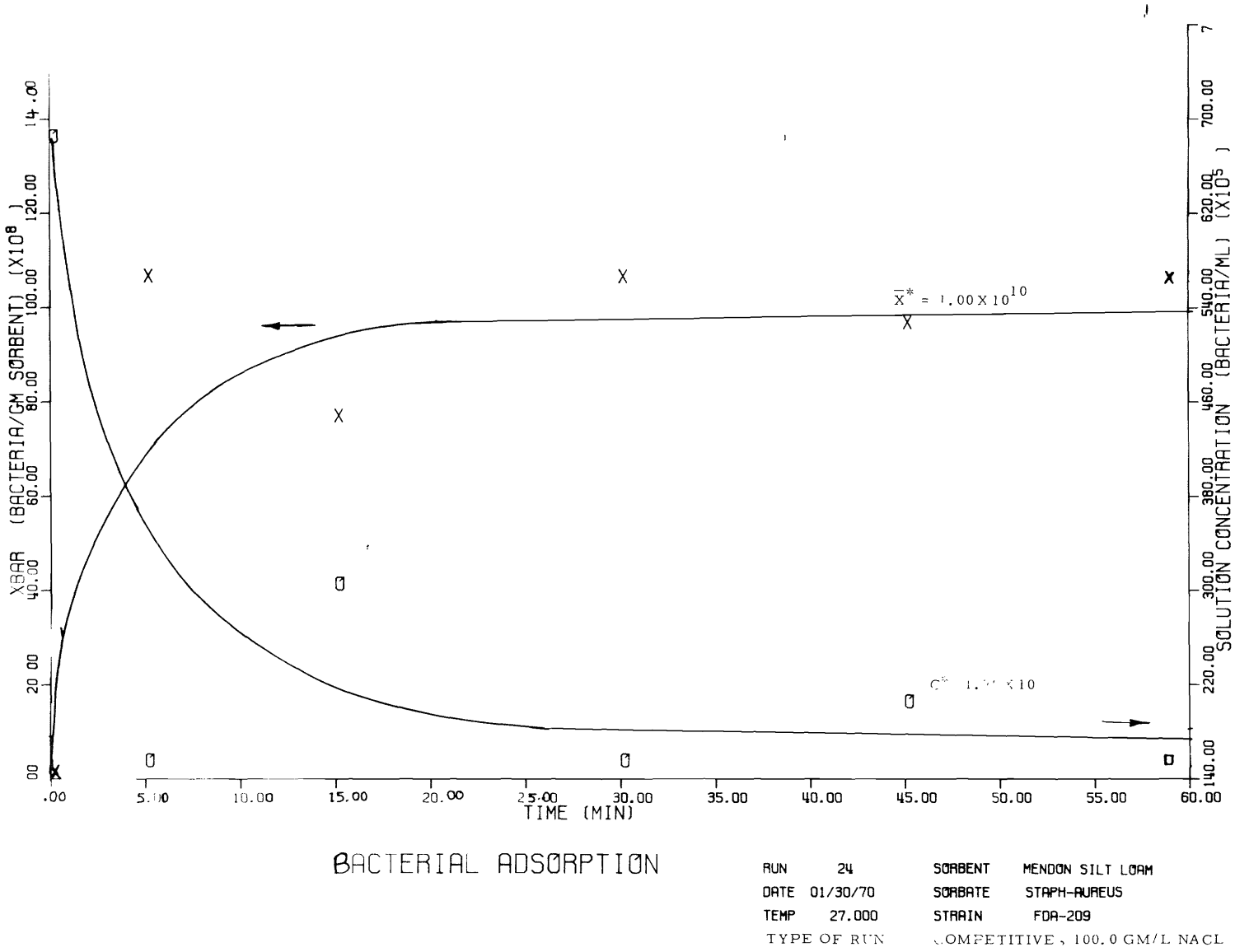


Figure B-9. Output from BACTXT-bacterial depletion and uptake curves by Gerber plotter.

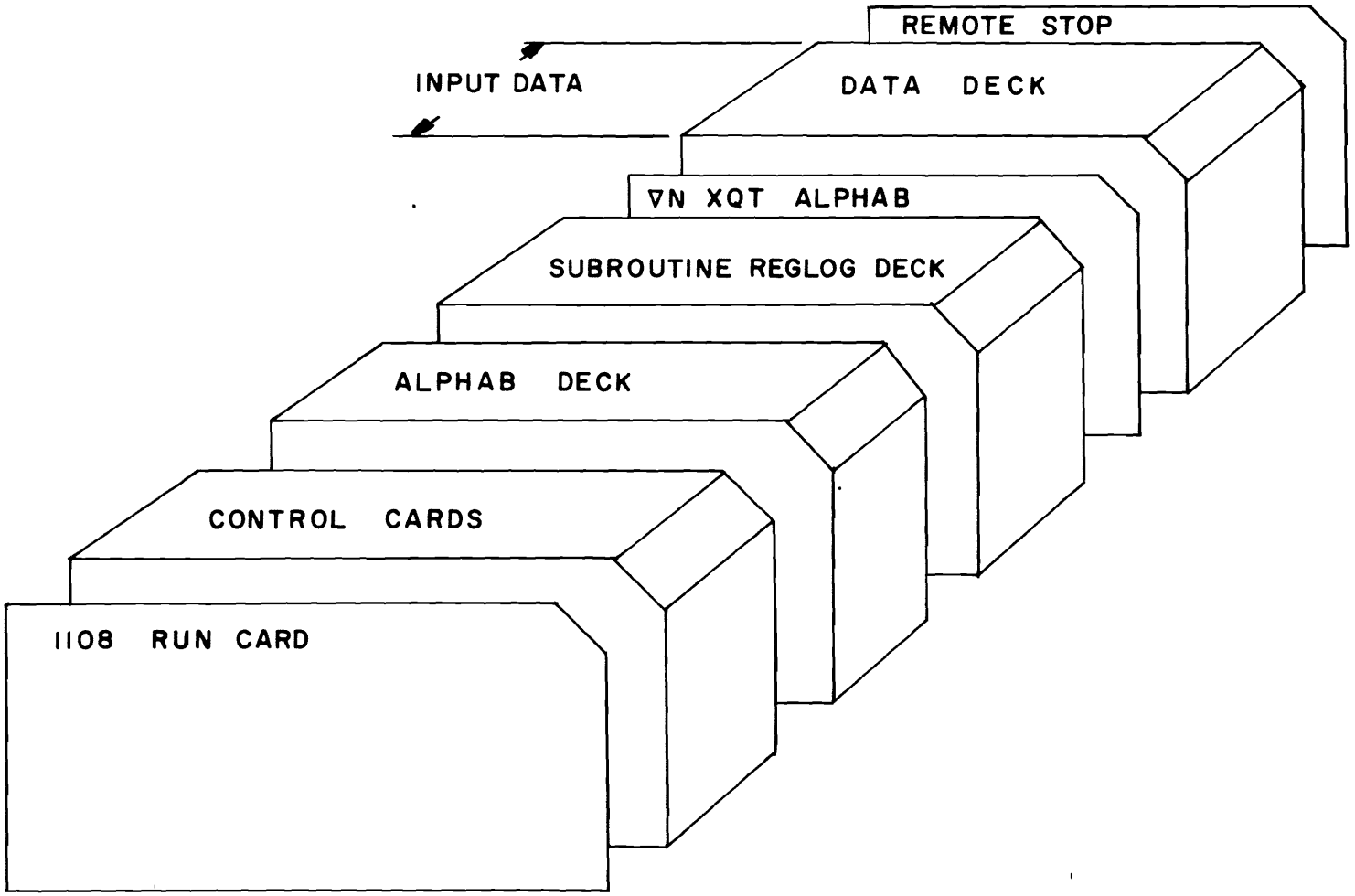


Figure B-10. Deck set-up for ALPHAB data input.

```
C     CALCULATION OF ALPHA AND XMAX FROM CSTAR AND XBARSTAR
C     PROJECT WG-82 BACTERIAL ADSORPTION ON SOILS
      DIMENSION CSSUM(40)
      DIMENSION CSTAR(40),XBARST(40),IRUNS(40), CSOXST(40)
      DIMENSION SDATE(40,2),        SRATE(3),STRAIN(2),SRENT(3),SKIND(3)
      DATA IDX,IDY/4HCSTR,4HXBST/
     2 READ(5,13)NRUNS,SRATE,STRAIN,SRENT,SKIND,TEMP,      (IRUNS(I),SDAT
     2E(I,1),SDATE(I,2),  CSTAR(I),XBARST(I),I=1,NRUNS)
   13 FORMAT(I6/3A6/2A6/3A6/3A6/F6.1/(I10,2A4,2F12.2))
      DO 705 I = 1,NRUNS
      CSSUM(I) = CSTAR(I)
  705 CONTINUE
      IRUNLO = IRUNS(1)
      IRUNHI = IRUNS(NRUNS)
      XNEG
      NPR=1
      NTX=1
      NTY=1
      CX=1
      CY=1
      DO 16 I=1,NRUNS
      CSOXST(I)=CSTAR(I)/XBARST(I)
   16 CONTINUE
      M = NRUNS
      CALL REGLOG(M,NP,NPR, IDX, IDY,CSTAR,CSOXST,NTX,NTY,CX,CY,YINCEP,
     2SLOPE,R,ISQ)
C     CSTAR=IDX,CSOXST=IDY,CSTAR=X,CSOXST=Y,YINCEPT=A,SLOPE=B
      XMAX=1./SLOPE
      ALPHA=1./(YINCEP*XMAX)
      WRITE(6,3F3)
  953 FORMAT(1H1////20X*'DETERMINATION OF ALPHA AND XMAX BY REGRESSION AN
     2ALYSIS OF LINEARIZED LANGMUIR ISOTHERM*')
      WRITE(6,954)SDATE(1,1),SDATE(1,2),SRATE,IRUNLO,IRUNHI,STRAIN,SRENT
     2,SKIND,TEMP,R,ISQ,YINCEP,SLOPE,ALPHA,XMAX
  954 FORMAT(1H0///40X'DATE OF RUN 1 = ',2A4, 7X'SORBATE',2X,3A6/40X'RUN
     1S',I6,2X'TO',I6,2X,2A6/71X'SORBENT',3A6/78X,3A6/74X'TEMP',F6.1,
     2X'DEG. CENT.'////
     3 20X'REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS'//45X'R =
     4',F6.2 /43X'ISQ =',F6.3 /19X'YINTERCEPT = 1/(ALPHA*XMAX) =',E12.6/
     520X'SLOPE OF BEST FIT =',E12.6/41X'ALPHA =',E12.6/42X'XMAX =',E12.
     66///35X'BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS'//45X'RUN
     7S',2X'DATE EXP BEGUN',7X'C',6X'XBAR',5X'C/XBAR')
      WRITE(6,955)(IRUNS(I),SDATE(I,1),SDATE(I,2),  CSTAR(I),XBARST(I),C
     2SOXST(I),I=1,NRUNS)
  955 FORMAT(42X,I5,6X,2A4,F14.5,E12.5,E15.5)
C     BEGIN OPERATION OF PLOTTER TO PLOT (CSTAR/XBSTAR) VS CSTAR
C     STEP 1 ESTABLISH DIMENTIONS OF PLOT PAPER
      CALL IOPLOT(14.0,10.0)
C     STEP 2 PROVIDE MAILING INSTRUCTIONS
      CALL SYMBL4(0.2,0.0,0.10,94HMAIL TO D. W. HENDRICKS, UWRL, UTAH
     2STATE UNIV., LOGAN, UTAH 84321  SEND BY FIRST CLASS MAIL,90.0,94)
C     STEP 3  ESTABLISH PERMANENT ORGIN FOR GRAPH.  THIS IS DONE BY (-)
      CALL PLOT(1.5,2.0,-3)
C     STEP 4  ESTABLISH X-AXIS, THEN Y-AXIS -LABEL EACH AXIS
      ALX = 10.)
      ALY = 8.0
      KRUNS = NRUNS + 1
      CSTAR(KRUNS) = 0.
      CSOXST(KRUNS) = 0.
      CALL SCALE(CSTAR,KRUNS,ALX,CMIN,DSTAR,1)
      CALL AXIS (0.,0.,15HCSTAR (RUGS/ML),-15,ALX,0.0,CMIN,DSTAR)
      CALL SCALE(CSOXST,KRUNS,ALY,CSMIN,DCSX,1)
      CALL AXIS(0.0,0.0,14HCSTAR/XBARSTAR,14,ALY,90.0,CSMIN,DCSX)
C     STEP 5 SHOW THE EXPERIMENTAL POINTS
      CALL PLOT(0. ,0.0,3)
      DO 601 I = 1,NRUNS
  601 CALL SYMBL4(CSTAR(I),CSOXST(I),0.14,1HX,0.0,-1)
C     STEP 6 PLOT THE BEST FIT CURVE
      YZERO = (YINCEP-CSMIN)/DCSX
      XDI = .9*ALX
      XDIST = .8*ALX*DSTAR
      YMAX = YZERO + (SLOPE*XDIST)/DCSX
      CALL PLOT(0.0,0.0, 2)
      CALL PLOT(0.0,YZERO,3)
      CALL PLOT(XDI,YMAX,2)
      CALL PLOT(0.0,0.0, 3)
C     LABEL GRAPH WITH APPROPRIATE IDENTIFICATION INFORMATION
      CALL SYMBL4(0.0,-1.0,.2, 64HBACTERIAL ADSORPTION EXPERIMENTS -  LI
     2NEARIZED LANGMUIR ISOTHERM,0.0,64)
      CALL SYMBL4(0.0,-1.25,0.1,4HRUNS,0.0,4)
      CALL NUMBRI(0.3,-1.25,0.1,IRUNLO,0.0)
      CALL SYMBL4(0.7,-1.50,0.1,2HTO,0.0,2)
      CALL NUMBRI(0.3,-1.50,0.1,IRUNHI,0.0)
      CALL SYMBL4(0.0,-1.75,0.1),4HTEMP,0.0,4)
      CALL NUMBRF(0.4,-1.75,0.1),TEMP,0.0,3)
      CALL SYMBL4(0. ,-1.25,0.1),7HSORBATE,0.0,7)
      CALL SYMBL4(0.3,-1.25,0.1),SRENT,0.0,1)
      CALL SYMBL4(0.7,-1.50,0.1),7HSORBATE,0.0,7)
      CALL SYMBL4(0.4,-1.50,0.1),SRATE,0.0,1)
      CALL PLOT(-1.5,-1.0,-3)
      CALL FINI
C     BEGIN OPERATION OF PLOTTER TO PLOT XBAR* VS C* (LANGMUIR ISOTHERM)
C     STEP 1 ESTABLISH DIMENTIONS OF PLOT PAPER
      CALL IOPLOT(14.0,10.0)
C     STEP 2 PROVIDE MAILING INSTRUCTIONS
      CALL SYMBL4(0.2,0.0,0.10,94HMAIL TO D. W. HENDRICKS, UWRL, UTAH
     2STATE UNIV., LOGAN, UTAH 84321  SEND BY FIRST CLASS MAIL,90.0,94)
C     STEP 3  ESTABLISH PERMANENT ORGIN FOR GRAPH.  THIS IS DONE BY (-)
      CALL PLOT(1.5,2.0,-3)
C     STEP 4  ESTABLISH X-AXIS, THEN Y-AXIS -LABEL EACH AXIS
      NP = NRUNS + 1
      CSSUM(NP) = 0.
      XBARST(NP) = 0.
      ALX = 12.0
      ALY = 8.0
      CALL SCALE (CSSUM,NP,   ALX,CMIN,DSTAR,1)
      CALL AXIS (0.0,0.0,15HCSTAR (RUGS/ML),-15,ALX,0.0,CMIN,DSTAR)
      CALL SCALE (XBARST,NP,   ALY,XMIN,DXXX,1)
      CALL AXIS (0.0,0.0,18HXBARSTAR (RUGS/GM),18,ALY,90.0,XBMIN,DXXX)
C     STEP 5 SHOW THE EXPERIMENTAL POINTS
      CALL PLOT(0. ,0.0,3)
      DO 602 I = 1,NRUNS
```

Figure B-11. Program listing of ALPHAB.

```
  402 CALL SYMBL4(CSTAR(I),XBARST(I),0.14,1HX,0.0,1)
C     STEP 5 PLOT THE BEST FIT CURVE
      CINCH = 0.
      JK = 1
      CALL PLOT(0.0,0.0,3)
      AXO = ALPHA*XMAX*DSTAR
      DO 403 JK = 1,200
      CINCH = CINCH + 0.05
      YINCH = AXO*CINCH/(DXXX*(1.+ALPHA*CINCH*DSTAR))
      CALL PLOT (CINCH,YINCH,2)
  403 CONTINUE
C     LABEL GRAPH WITH APPROPRIATE IDENTIFICATION INFORMATION
      CALL SYMBL4(2.0,-1.0,.2,52HBACTERIAL ADSORPTION EXPERIMENTS - LANG
     2MUIR ISOTHERM,0.0,52)
      CALL SYMBL4(4.0,-1.25,0.10,4HRUNS,0.0,4)
      CALL NUMBRI(4.7,-1.25,0.10,IRUNLO,0.0)
      CALL SYMBL4(4.2,-1.50,0.10,2HTO,0.0,2)
      CALL NUMBRI(4.3,-1.50,0.10,IRUNHI,0.0)
      CALL SYMBL4(4.0,-1.75,0.10,4HTEMP,0.0,4)
      CALL NUMBRF(4.4,-1.75,0.10,TEMP,0.0,3)
      CALL SYMBL4(6.0,-1.25,0.10,7HSORBENT,0.0,7)
      CALL SYMBL4(6.8,-1.25,0.10,SBENT,0.0,10)
      CALL SYMBL4(6.0,-1.50,0.10,7HSORBATE,0.0,7)
      CALL SYMBL4(6.8,-1.50,0.10,SBATE,0.0,10)
      CALL PLOT(-1.0,-1.0,-3)
      CALL FINI
   81 CONTINUE
      IF(NLTOPT.LT.1)GO TO 82
      NYE1
      NMP=0
      LP=0
      DATA YAXIS,XAXIS/8HXBARST,5HCSTAR/
      XMIN=0.
      P=0.
      YZ=10.E+09
      IC=14
C     CALL POTPLT(SCXX,NRUNS,NY,NMP,LP,CSTAR,XMIN,XBARST,P,YZ,YAXIS,
C    2XAXIS,IC)
      DATA ZAXIS,XAXIS/8HCSOXST,5HCSTAR/
      YZ=25.E-02
      P=-3.
C     CALL POTPLT(SCXX,NRUNS,NY,NMP,LP,CSTAR,XMIN,COSXST,P,YZ,ZAXIS,
C    2XAXIS,IC)
      CONTINUE
   82 GO TO 2
      END

      SUBROUTINE REGLOG(N,NN,NPR,IDX,IDY,X,Y,NTX,NTY,CX,CY,A,B,R2)
C     REGRESSION EQUATIONS FOR DIFFERENT LOG AND SEMI LOG TRANSFORMS
C     TRANSFORMS (NTX OR NTY) ARE AS FOLLOWS--
C        1 = NO TRANSFORMATION
C        2 = LOG10(Z)
C        3 = LOG10(CZ-Z)
C        4 = LOG10(Z(N)-Z(I))
C        5 = TRANSFORM 2 WITH REGRESSION ABOUT LOG10(ZBAR)
C        6 = TRANSFORM 3 WITH REGRESSION ABOUT LOG10(CZ-Z MEAN)
C        7 = TRANSFORM 4 WITH REGRESSION ABOUT LOG10(Z(N)-Z(I) MEAN)
C     N IS THE TOTAL NUMBER OF OBSERVATIONS, I E THE SIZE OF THE X AND
C        Y ARRAYS
C     NN IS THE NO OF TAIL END OBSERVATIONS THAT ARE USED IN COMPUTING
C        Z(N) ASSOCIATED WITH TRANSFORMATION 4 OR 7
C     NPR IS A PRINT OPTION FOR PRINTING THE ORIGINAL DATA AND THE
C        TRANSFORMED DATA IF NPR IS NON ZERO
C     IDX IS A 4 CHARACTER ALPHANUMERIC IDENTIFICATION FOR X
C     IDY IS A 4 CHARACTER ALPHANUMERIC IDENTIFICATION FOR Y
C     X IS THE INDEPENDENT VARIABLE ARRAY
C     Y IS THE DEPENDENT VARIABLE ARRAY
C     NTX IS THE TRANSFORMATION SPEC FOR X
C     NTY IS THE TRANSFORMATION SPEC FOR Y
C     CX AND CY ARE THE CONSTANTS ASSOCIATED WITH TRANSFORMATIONS 3
C        AND 6
      DIMENSION X(N),Y(N)
      SXN=0.
      SYN=0.
      SX=0.
      SY=0.
      SXY=0.
      SX2=0.
      SY2=0.
      AN=NN
      IF(NPR.EQ.1)WRITE(6,124)IDX,IDY
  124 FORMAT(1H1,25X*ORIGINAL DATA FOLLOWS*/* OBS NO*17X4A4,7X4A4)
      DO 5 I=1,N
      IF(NPR.EQ.1)WRITE(6,125)I,X(I),Y(I)
  125 FORMAT(1X15,2E20.8)
      IF(NTX.GT.4) SX=SX+X(I)
      IF(NTY.GT.4) SY=SY+Y(I)
    5 CONTINUE
      IF(NTX.EQ.4.OR.NTX.EQ.7) GO TO 2
      GO TO 4
    2 DO 3 I=1,NN
    3 SXN=SXN+X(N-I+1)
      CX=SXN/AN
      NEN-NN
    4 IF(NTY.EQ.4.OR.NTY.EQ.7) GO TO 17
      GO TO 16
   17 DO 14 I=1,NN
   14 SYN=SYN+Y(N-I+1)
      CY=SYN/AN
      IF(NTY.NE.4.OR.NTX.NE.7) NEN-NN
   16 AN=N
      IF(NTX.GT.1.OR.NTY.GT.1.AND.NPR.EQ.1)WRITE(6,126)IDX,IDY
  126 FORMAT(1H0,25X*TRANSFORMED DATA FOLLOWS*/*  OBS NO*9X4A4,7(15X4A4))
      DO 20 I=1,N
      GO TO (17,6,7,8,9,7,7),NTX
    6 IF(X(I).LE.0.) GO TO 8
      IF(NPR.EQ.1)XT=X(I)
      X(I)=ALOG10(X(I))
      GO TO 10
    7 X(I)=CX-X(I)
      GO TO 6
    8 WRITE(6,120)IDX,I,NTX
  120 FORMAT(1X,A4,* VALUE FOR I = *I5,* IS IMPROPER FOR TRANSFORM = *I5
     1,*.  VALUE SET AT ZERO*)
      X(I)=0.
   10 GO TO(15,11,12,12,11,12,12),NTY
   11 IF(Y(I).LE.0.) GO TO 13
      IF(NPR.EQ.1)YI=Y(I)
      Y(I)=ALOG10(Y(I))
      GO TO 15
   12 Y(I)=CY-Y(I)
```

Figure B-11. Continued.

```
      GO TO 11
   13 WRITE(6,120)IDY,I,NTY
      Y(I)=0.
   15 IF(NTX.LE.4) SX=SX+X(I)
      IF(NTY.LE.4) SY=SY+Y(I)
      IF(NTX.GT.1.OR.NTY.GT.1.AND.NOR.EQ.1)WRITE(6,127)I,XI,YI,X(I),Y(I)
  127 FORMAT(1X,I5,4E20.8)
   20 CONTINUE
      GO TO (21,21,21,21,22,23,23),NTX
   21 XBAR=SX/AN
      GO TO 25
   22 XBAR=ALOG10(SX/AN)
      GO TO 25
   23 XBAR=ALOG10(ABS(CX-(SX/AN)))
   25 GO TO(26,26,26,26,27,28,28),NTY
   26 YBAR=SY/AN
      GO TO 29
   27 YBAR=ALOG10(SY/AN)
      GO TO 29
   28 YBAR=ALOG10(ABS(CY-(SY/AN)))
   29 DO 30 I=1,N
      XX=X(I)-XBAR
      YY=Y(I)-YBAR
      SXY=SXY+XX*YY
      SX2=SX2+XX*XX
   30 SY2=SY2+YY*YY
      SDX=SQRT(SX2/(AN-1.))
      SDY=SQRT(SY2/(AN-1.))
      SCX=1./SDX
      SCY=1./SDY
C     CALCULATE REGRESSION COEFFICIENTS
      B=SDY/SDX
      IF(SXY.LT.0.)B=-B
      A=YBAR-B*XBAR
      C=A/B
      D=1./B
      R=SXY/SQRT(SX2*SY2)
      R2=R*R
      RC=SQRT(ABS(R))
      B1=SXY/SX2
      A1=YBAR-B1*XBAR
      D1=SXY/SY2
      C1=XBAR-D1*YBAR
C     WRITE OUT RESULTS
      WRITE(6,121)
  121 FORMAT(1H1,25X'ORTHOGONAL REGRESSION EQUATIONS')
      WRITE(6,110)IDX,NTX,SCX,XBAR,IDY,NTY,SCY,YBAR
  110 FORMAT(1HO,'X = 'A4,' TRANS'I2,' SCALED BY'E12.6,' ABOUT MEAN = 'E
     112.6,' Y = 'A4,' TRANS'I2,' SCALED BY'E12.6,' ABOUT MEAN = 'E12.6)
      IF(NTX.GT.2.OR.NTY.GT.2)WRITE(6,123)IDX,CX,IDY,CY
  123 FORMAT(1XA4,' CX ='E15.8,5XA4,' CY ='E15.8)
      WRITE(6,111)IDY,A,B,IDX
  111 FORMAT(1HO,A4,' = 'E15.8,' + ('E15.8,') * 'A4)
      WRITE(6,111)IDX,C,D,IDY
      IF(NTX.EQ.1) GO TO 40
      XA=10.**C
      XB=10.**XBAR
      WRITE(6,112)IDX,XA,XB,NTX
  112 FORMAT(1HO,A4,' INTERCEPT ='E15.8,' THROUGH 'E15.8,' WITH INVERSE
     1TRANSFORM OF'I2)
   40 IF(NTY.EQ.1) GO TO 50
      YC=10.**A
      YBR=10.**YBAR
      WRITE(6,112)IDY,YC,YBR,NTY
   50 SYGX=SQRT(((1.-R2)*(SY2))/(AN-1.))
      SXGY=SQRT(((1.-R2)*(SX2))/(AN-1.))
      WRITE(6,122)
  122 FORMAT(1HO,25X'ORDINARY REGRESSION EQUATIONS')
      WRITE(6,113)IDX,SDX,SXGY,IDY,SDY,SYGX
  113 FORMAT(1HO'X = 'A4,' WITH STDEV ='E15.8,' AND SX/Y ='E15.8,5X'Y =
     1'A4,' WITH STDEV ='E15.8,' AND SY/X ='E15.8)
      WRITE(6,111)IDY,A1,B1,IDX
      WRITE(6,111)IDX,C1,D1,IDY
      IF(NTY.EQ.1) GO TO 55
      XA1=10.**C1
      WRITE(6,112)IDX,XA1,XBB,NTX
   55 IF(NTY.EQ.1) GO TO 60
      YC1=10.**A1
      WRITE(6,112)IDY,YC1,YBB,NTY
   60 WRITE(6,115)RC,R2,N
  115 FORMAT(1HO,'RC ='E8.5,5X'R2 = 'E8.5,5X'RE = 'E8.5,5X'E(OUT 'I5,' OB
     1SERVATIONS USED IN CALCULATING EQUATIONS')
      RETURN
      END
```

Figure B-11. Continued.

BACTERIAL ADSORPTION
DERIVATION OF ALPHA AND XMAX FROM REG. ANAL. OF LINEARIZED ISOTHERM

Variable Name	Field
NRUNS	(I6)
SBATE	(7A2)
STRAIN	(2A6)
SBENT	(3A6)
SKIND	(3A6)
TEMP	(F6.1)

FORM | STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

NRUNS = 6
SBATE = STAPH-AUREUS
STRAIN = FDA-209
SBENT = SØIL
SKIND = MENDØN SILT LØAM
TEMP = 37.

RUN(I) (I10)	SDATE(I) (2A4) mo. day yr.	CSTAR(I) (E12.2)	XBARST(I) (E12.2)
1	01/16/70	8.00E07	2.50E10
2	01/16/70	5.50E07	2.50E10
3	01/16/70	3.30E07	2.50E10
4	01/16/70	2.00E07	2.40E10
8	01/20/70	15.00E07	2.80E10
9	01/20/70	10.00E07	2.50E10
	/ /	.E	.E
	/ /	.E	.E
	/ /	.E	.E
	/ /	.E	.E
	/ /	.E	.E
	/ /	.E	.E
	/ /	.E	.E
	/ /	.E	.E

*A standard card form, IBM electro 88857, is available for punching statements from this form

Figure B-12. IBM coding sheet for recording the equilibrium data.

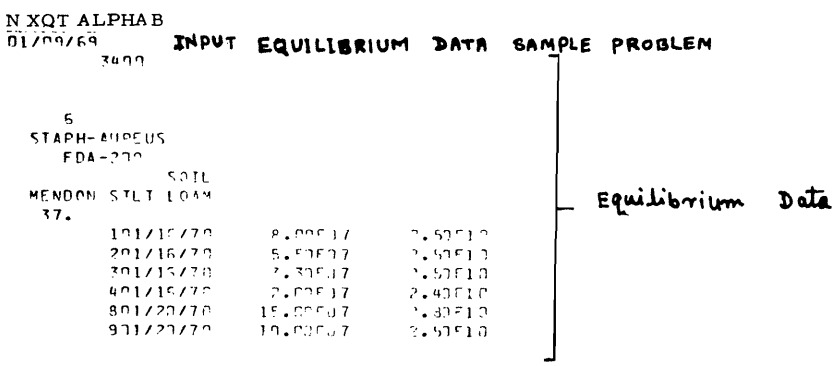


Figure B-13. Listing of equilibrium data.

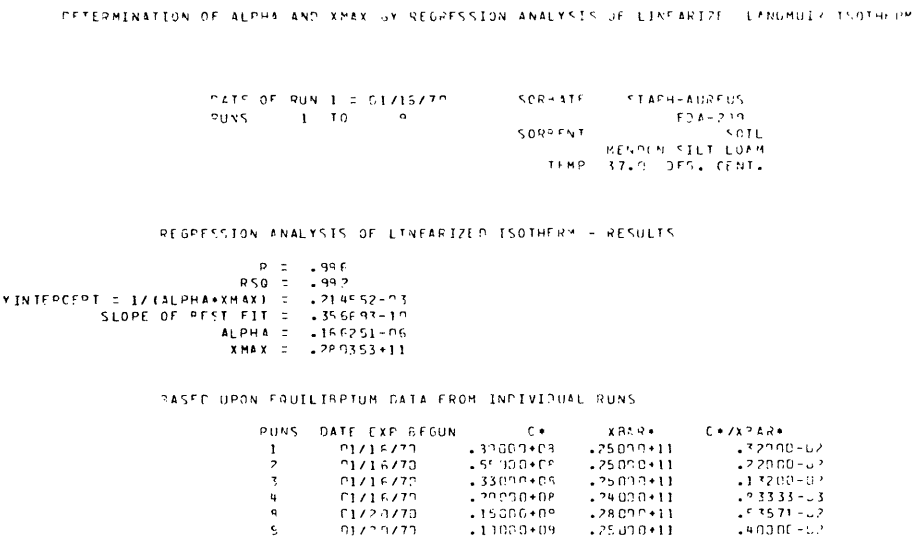


Figure B-14. Output from ALPHAB-tabular printout.

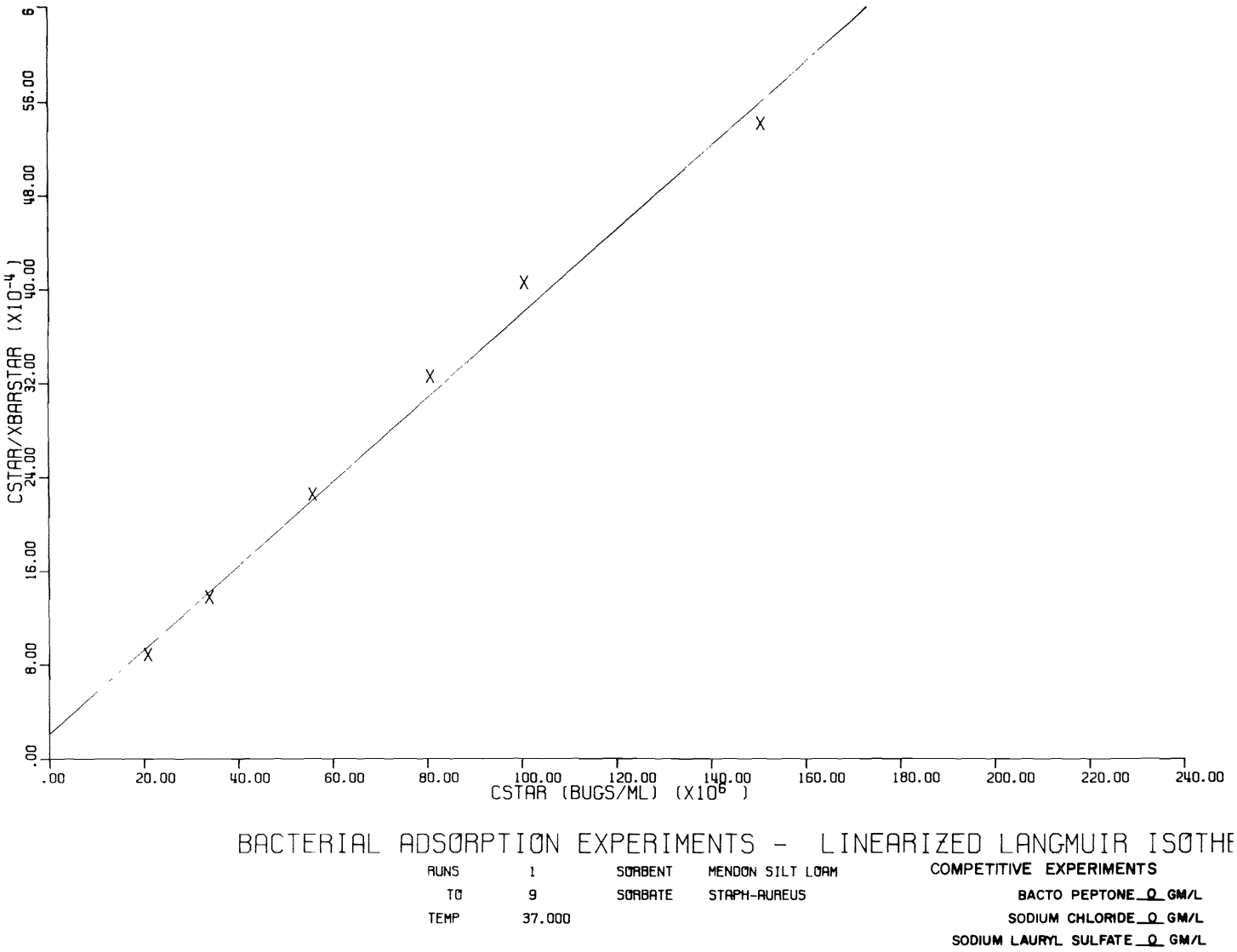


Figure B-15. Output from ALPHAB-linearized Langmuir isotherm by Gerber plotter.

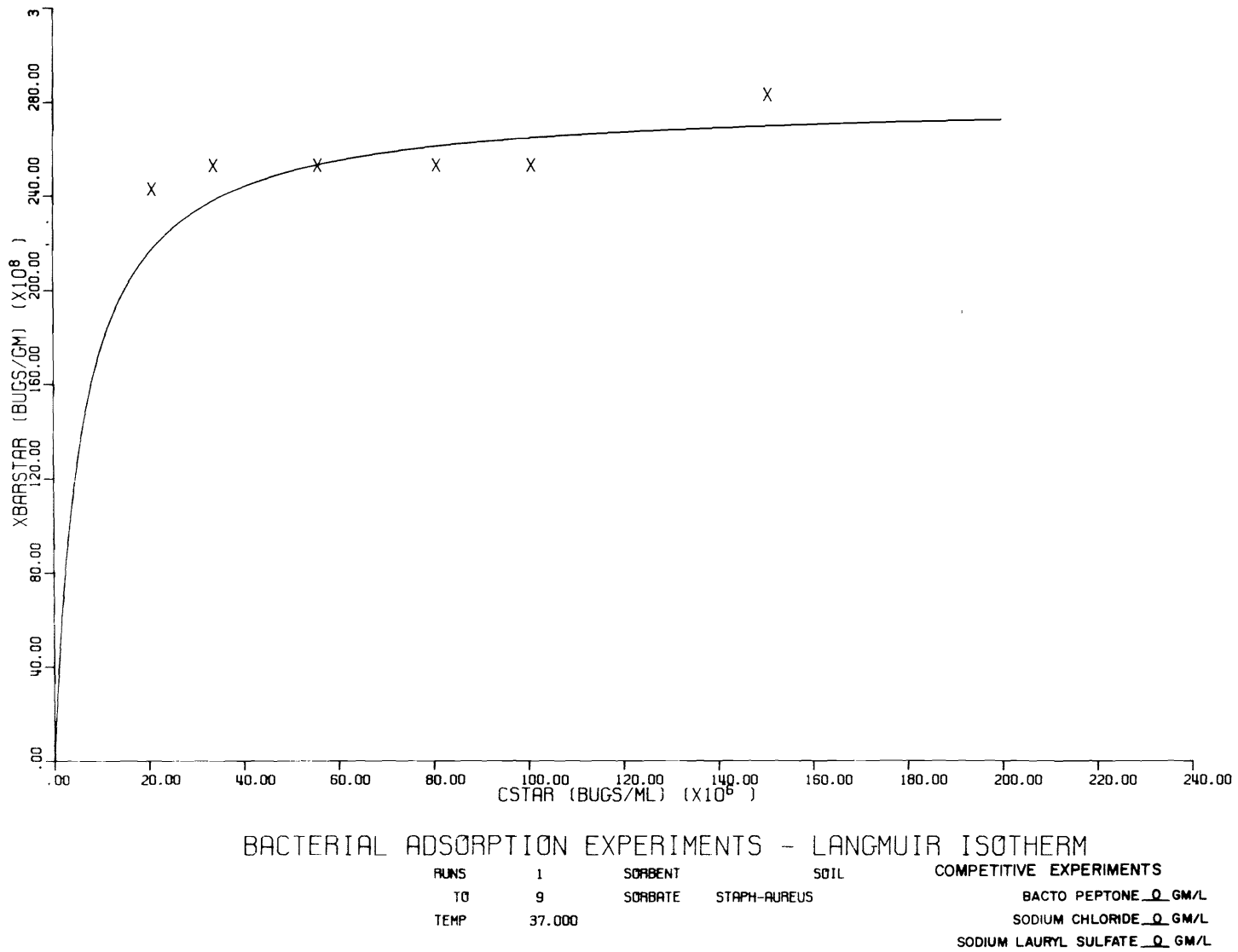


Figure B-16. Output from ALPHAB-conventional Langmuir isotherm by Gerber plotter.

APPENDIX C

THRESHOLD TOXIC AND COMPETITIVE LEVELS

Toxicity of chemical sorbates to S. aureus

The results of tests to determine threshold toxicity concentrations of SLS, peptone, and sodium chloride to *S. aureus* are outlined below. For each test a control containing only distilled water and *S. aureus* was used. Partial results of the toxicity tests for each of these chemicals have been compiled separately as Figures C-10-C-15, C-16-C-19, and C-20-C-25, respectively. Assays were done at the end of one hour contact time.

Sodium lauryl sulfate. Figure C-1 summarizes the results of tests for determining the toxic effect of SLS on *S. aureus.* Figure C-1 shows a marked effect on cell viability is caused by increasing SLS concentration; the threshold point of significant toxic effect appears to be .05 gram per liter. It should be noted that 0.5 gram per liter SLS caused 100 percent depletion of bacteria from solution (Figure C-1). Figures C-6 to C-11 show the data on which Figure C-1 is based.

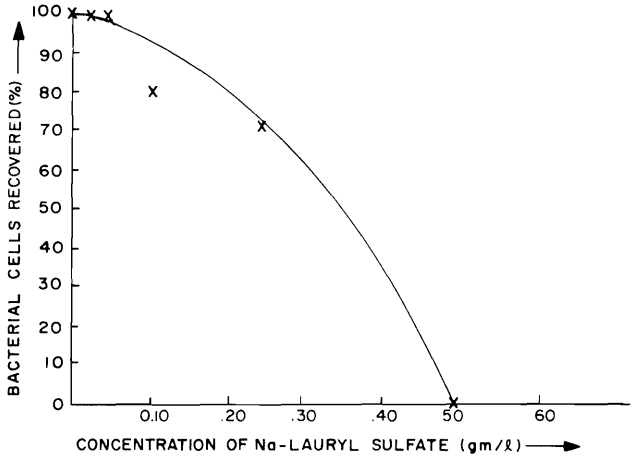


Figure C-1. Toxic effect of Na-lauryl sulfate on *S. aureus* at 27C.

Peptone. Figure C-2 shows the results of toxicity testing between *S. aureus* and peptone at concentrations of 1.0, 10.0, and 30.0 grams per liter. Even at a peptone concentration of 30 grams per liter, Figure C-2 shows no indication of toxicity. This concentration level is substantially higher than any levels which could be encountered under even the most adverse conditions. Therefore, peptone toxicity was not a problem for these tests. Figures C-12 to C-15 show data on which Figure C-2 is based.

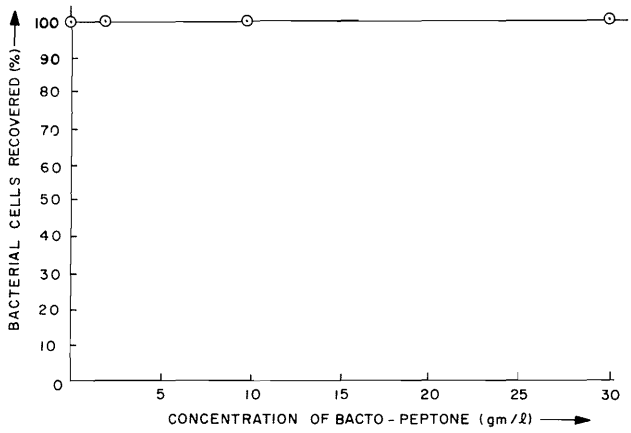


Figure C-2. Toxic effect of peptone on *S. aureus* at 27C.

Sodium chloride. Results in Figure C-3 indicate that no depletion in bacterial population occurred until NaCl concentration was increased beyond 100 grams per liter. Since this concentration value is also beyond practical experimental limits, sodium chloride toxicity was not a problem for these tests. Figures C-16 to C-21 show data on which Figure C-3 is based.

Threshold competitive levels of chemical adsorbates

The results of tests to determine the competitive effect of SLS, peptone, and NaCl on bacterial adsorption are discussed below. These tests were conducted to determine the concentration levels of each of these chemicals at which substantial impairment of bacterial adsorption occurs; this level is designated "threshold competitive level." Results of selected runs involving bacterial competition with each of these chemicals have been grouped separately as Figures C-22-C-25, C-26-C-31, and C-31-C-37, respectively.

Sodium lauryl sulfate. Even though .05 gram per liter of SLS showed no competition with bacteria for

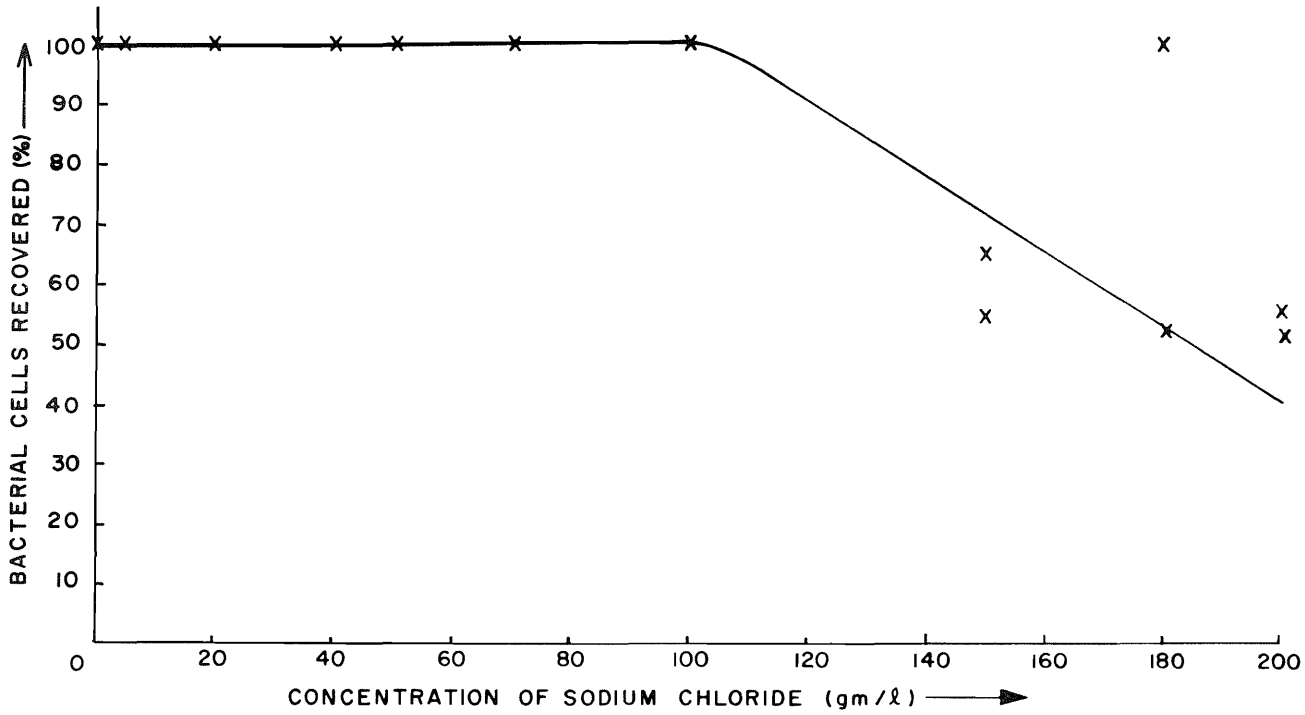


Figure C-3. Toxic effect of sodium chloride on *S. aureus* at 27C.

adsorption at 27C (Figures C-22-C-25), this concentration was selected to determine the adsorption isotherms at 10C, 20C, and 37C, since higher SLS concentrations proved to be toxic to *S. aureus* (Figure C-1). Using this SLS concentration (.05 gram per liter), a noticeable cell uptake occurred at 27C (Figure E-9) but when the temperature was lowered to 10C, no bacterial adsorption was observed (Figure E-2). This suggests that .05 gram per liter of SLS inhibits the bacterial adsorption at 10C but not at 27C.

Though no bacterial uptake occurred at 10C in .05 gram per liter of SLS solution, significant adsorption did occur (Figure E-5) at this temperature when the initial cell concentration was decreased by tenfold (1×10^7 cells/ml) and that of SLS was cut down by one-fifth (.01 gram per liter).

Peptone. Figure C-4 shows the effect of peptone competition with *S. aureus* for adsorption. These results were obtained using identical conditions in each test except for the peptone concentration. Figure C-14 shows zero uptake of cells at peptone concentrations greater than 6 grams per liter. As can be seen from Figure C-4, bacterial uptake was decreased linearly with increasing concentrations of peptone. A peptone level of 3.8 grams per liter, based on the results in Figure C-4, was chosen to study peptone's competitive effect on bacterial adsorption. However, no cell uptake was observed at 10C in the presence of peptone (3.8 grams per liter) as indicated in Figure F-2. Figure C-4 is based on results shown in Figures C-26 to C-31.

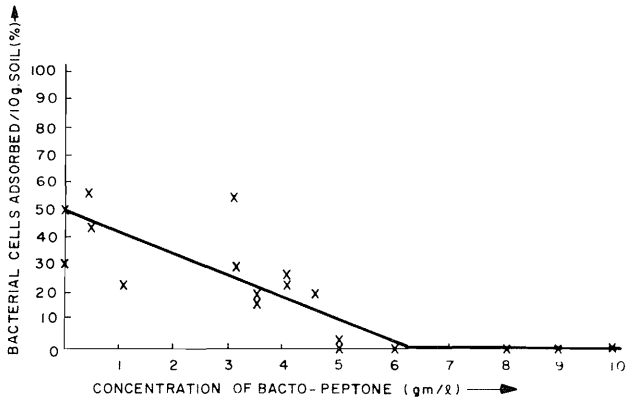


Figure C-4. Effect of various concentrations of peptone on bacterial adsorption at 27C.

Sodium chloride. A wide NaCl concentration range (.06 gram to 200 grams per liter) was tested to determine its ability to compete with bacteria for sorption sites. Results of these experiments are shown in Figure C-5, which indicate no competition of NaCl with bacteria for sorption. NaCl is a strong electrolyte and tends to remain in solution rather than go towards the interface. Bacterial cells are proteins which have hydrophilic as well as hydrophobic groups. The hydrophobic group might influence bacteria to tend towards the soil-solution interface, possibly resulting in their adsorption on soil

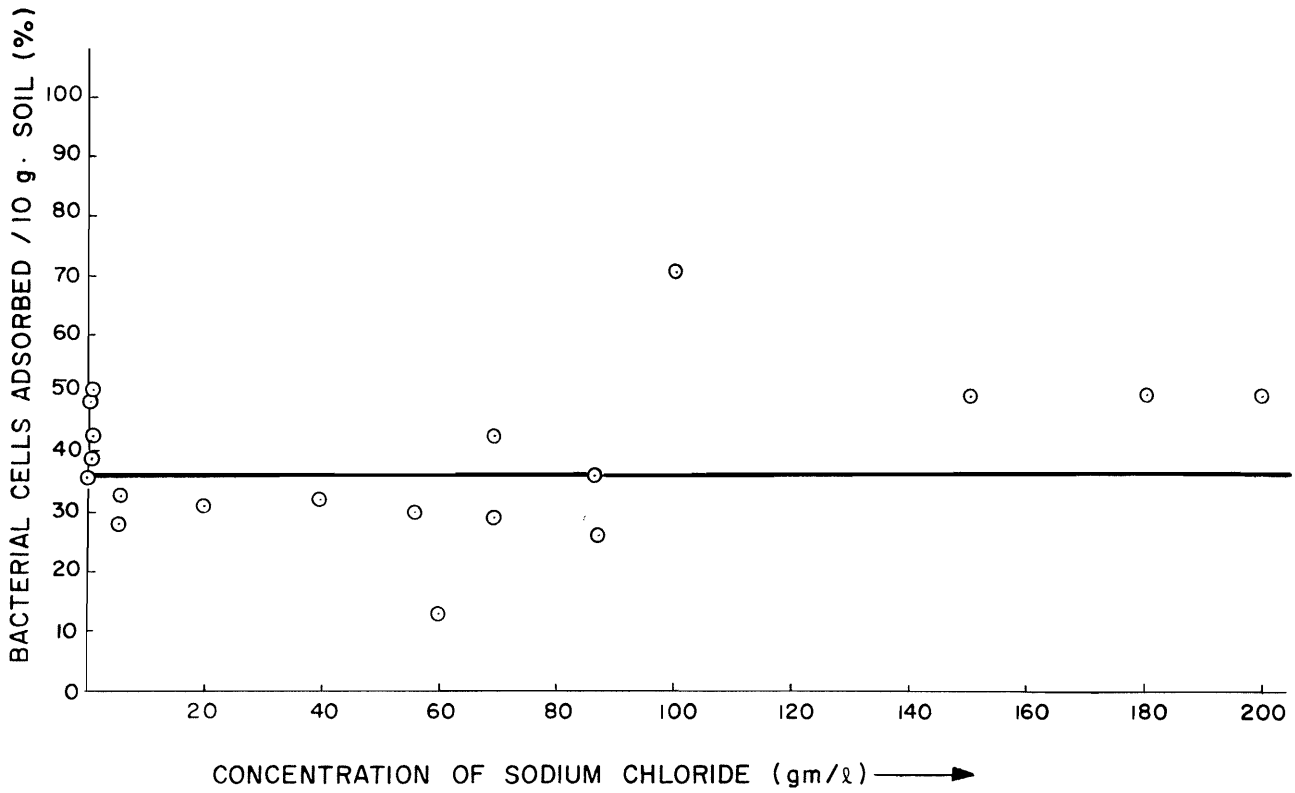


Figure C-5. Effect of various concentrations of sodium chloride on bacterial adsorption at 27C.

particles. Even if Na^+ is adsorbed, which is quite likely, its hydrated radius (0.98A°) is comparatively smaller than that of bacteria (100A°), suggesting that Na^+ may not be occupying all the space provided by adsorption sites but could leave enough room for bacterial cells to adsorb. Thus NaCl could be acting noncompetitive to bacteria. Bacterial cells are amphoteric in nature, i.e., individual cells have both positive as well as negative charges. If it is assumed that bacteria are preferentially adsorbed by soil particles they might have formed a coating around the soil particles, which left positive ends outside, that could possibly have caused Na^+ to repel from sorption sites. This could explain the noncompetitive behavior of Na^+. Though no competitive level of NaCl was observed experimentally, 30 grams per liter of NaCl concentration was selected for investigating adsorption isotherms at different temperatures. Figures C-32 to C-37 show results on which Figure C-5 is based.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 10/29/69
HOUR 1500 HRS
RUN 6
TYPE OF RUN CONTROL

SORBATE STAPH-AUREUS FDA-209

SOL. VOL. 2000.0 ML

INITIAL CONC (SPECT READ) 20000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	1.	1.0	215. 0.	1.	215.	100.	21500.	0.
5.0	1.	1.0	200. 0.	1.	200.	100.	20000.	0.
15.0	1.	1.0	220. 0.	1.	220.	100.	22000.	0.
30.0	1.	1.0	215. 0.	1.	215.	100.	21500.	0.
45.0	1.	1.0	230. 0.	1.	230.	100.	23000.	0.
60.0	1.	1.0	210. 0.	1.	210.	100.	21000.	0.

Figure C-6. Computer output run 6—sodium lauryl sulfate toxicity, control run, 0 gm/l SLS.

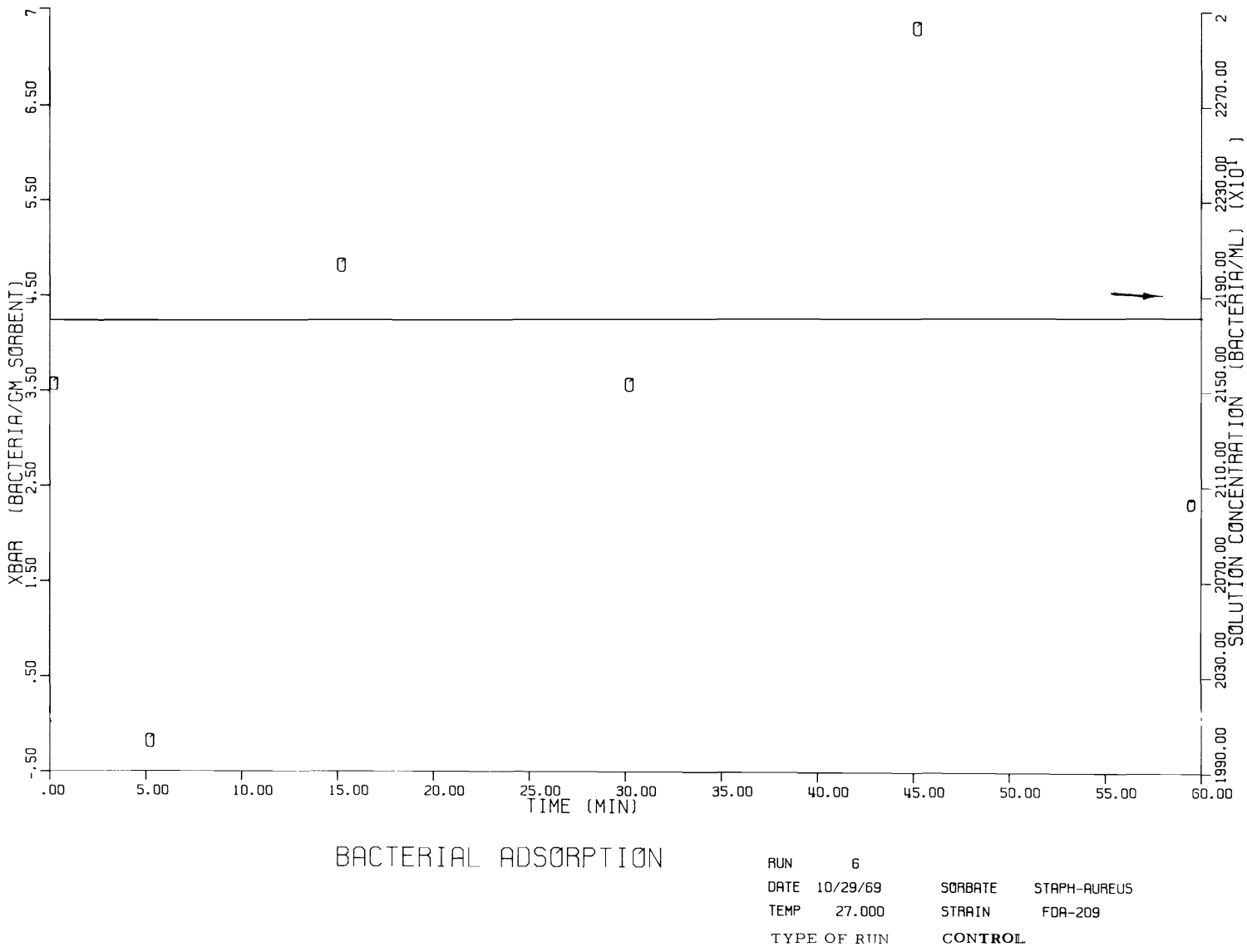


Figure C-7. Graphical output run 6—sodium lauryl sulfate toxicity, control run, 0 gm/l SLS.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 09/22/69
HOUR 1500 HRS
RUN 5
TYPE OF RUN TOXICITY

SORBATE STAPH-AUREUS FDA-209 LAURYL-SULFATE 0.05GM/L
SOL. VOL. 2000.0 ML
INITIAL CONC (SPECT READ) 20000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	1.	1.0	225. 0.	1.	225.	100.	20250.	0.
5.0	1.	1.0	230. 0.	1.	230.	100.	23000.	0.
15.0	1.	1.0	215. 0.	1.	215.	100.	21500.	0.
30.0	1.	1.0	225. 0.	1.	225.	100.	22500.	0.
45.0	1.	1.0	220. 0.	1.	220.	100.	22000.	0.
60.0	1.	1.0	195. 0.	1.	195.	100.	19500.	0.

Figure C-8. Computer output run 5—sodium lauryl sulfate toxicity, 0.06 gm/l SLS.

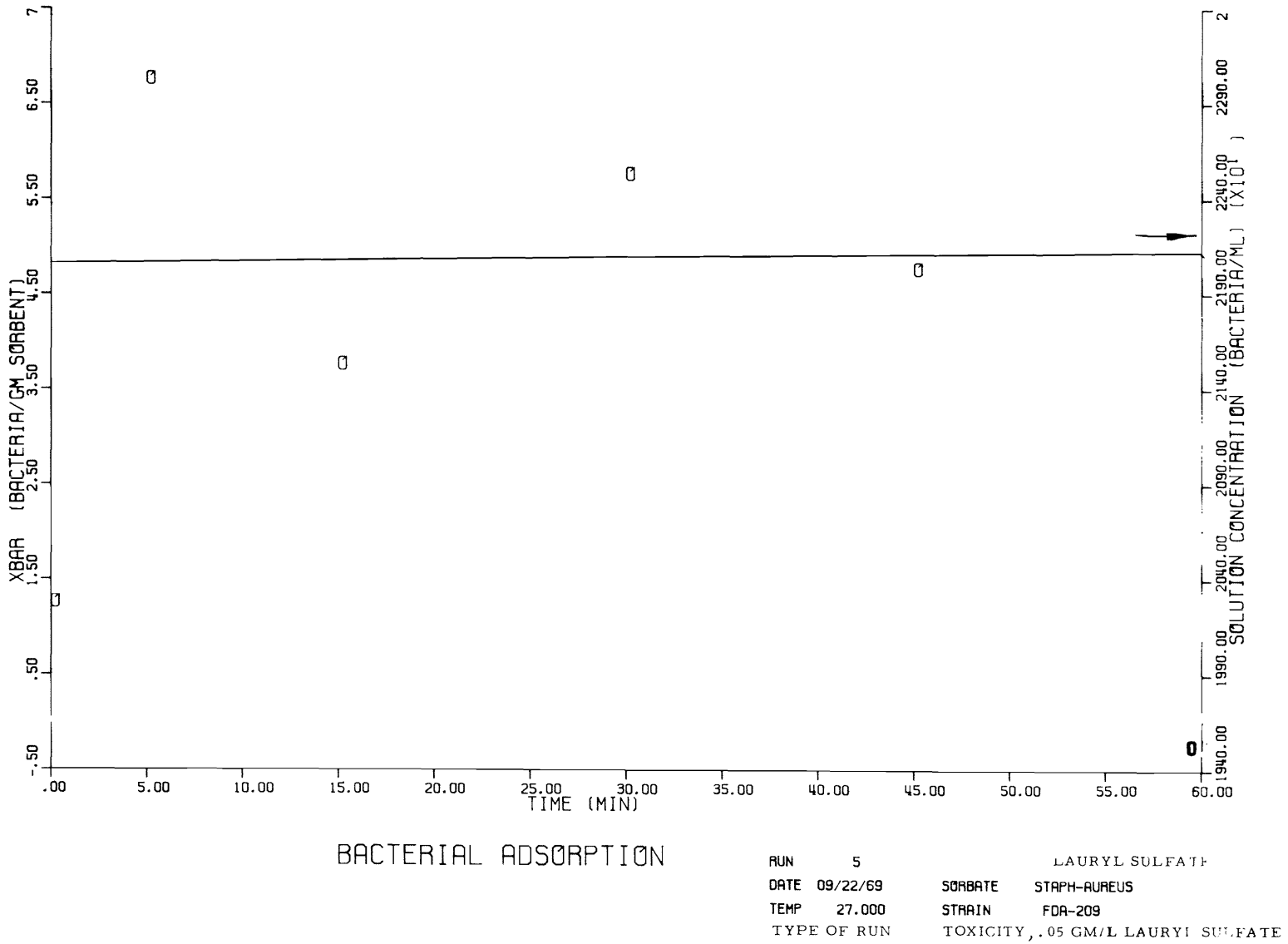


Figure C-9. Graphical output run 5—sodium lauryl sulfate toxicity, 0.05 gm/l SLS.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 09/22/69
HOUR 1500 HRS
RUN 8
TYPE OF RUN TOXICITY

SORBATE STAPH-SUREUS
FDA-209
LAURYL-SULFATE
0.50GM/L

SOL. VOL. 2000.0 ML

INITIAL CONC (SPECT READ) 20000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (UGS/ML)	XBAR (BUGS/GM)
.0	1.	1.0	275. 0.	1.	275.	100.	24750.	0.
5.0	1.	1.0	165. 0.	1.	165.	100.	16500.	0.
15.0	1.	1.0	70. 0.	1.	70.	100.	7000.	0.
30.0	1.	1.0	0. 0.	1.	0.	100.	0.	0.
45.0	1.	1.0	6. 0.	1.	6.	100.	600.	0.
60.0	1.	1.0	2. 0.	1.	2.	100.	200.	0.

Figure C-10. Computer output run 8—sodium lauryl sulfate toxicity, 0.50 gm/l SLS.

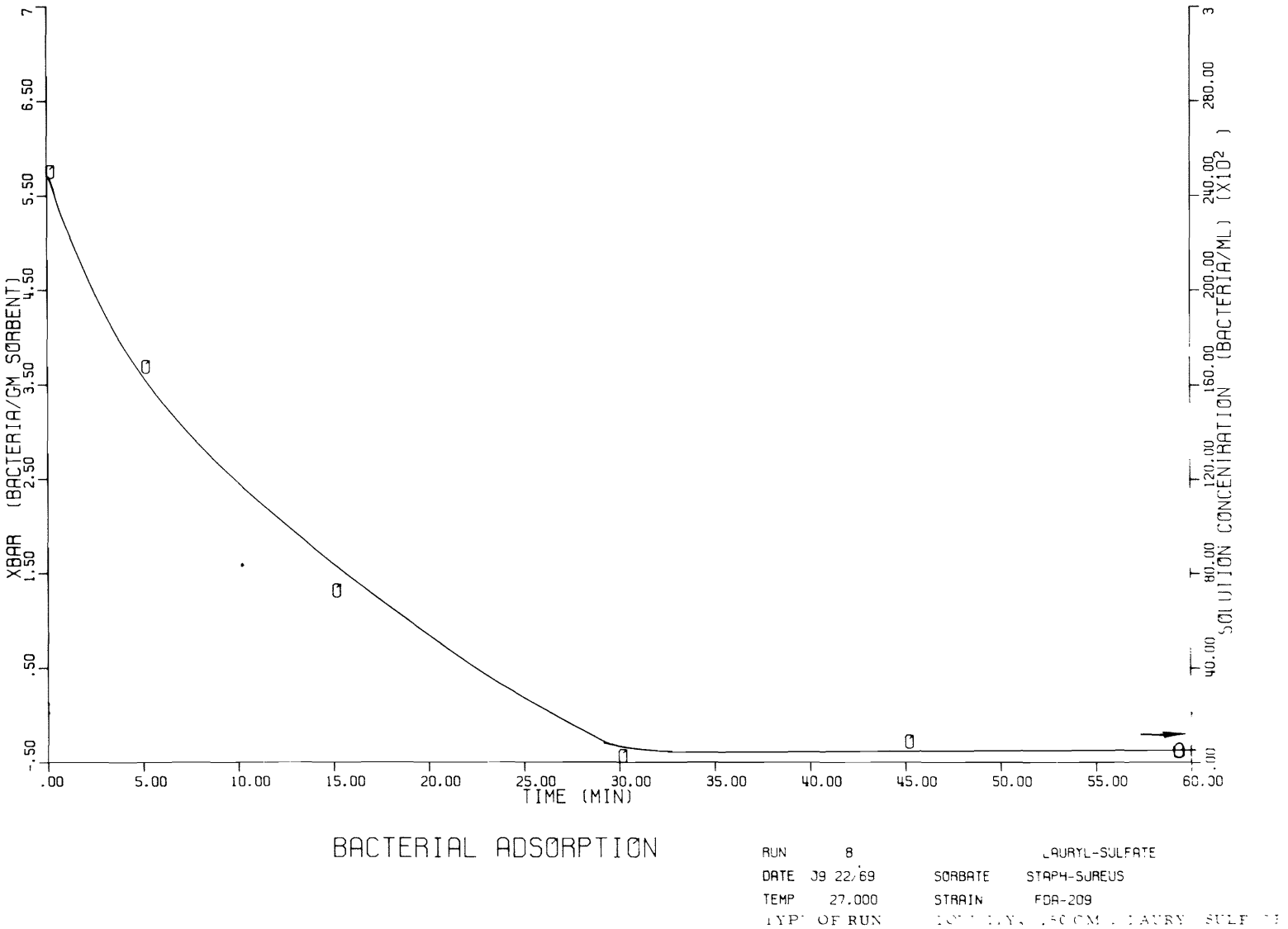


Figure C-11. Graphical output run 8—sodium lauryl sulfate toxicity, 0.50 gm/l SLS.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 09/23/69
HOUR 1500 HRS
RUN 12
TYPE OF RUN TOXICITY

SORBATE STAPH-AUREUS FDA-209
PEPTONE
10.000GM/L
SOL. VOL. 2000.0 ML
INITIAL CONC (SPECT READ) 20000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	1.	1.0	640. 0.	1.	640.	100.	67500.	0.
5.0	1.	1.0	710. 0.	1.	710.	100.	71000.	0.
15.0	1.	1.0	535. 0.	1.	535.	100.	53500.	0.
30.0	1.	1.0	585. 0.	1.	585.	100.	58500.	0.
45.0	1.	1.0	580. 0.	1.	580.	100.	58000.	0.
60.0	1.	1.0	610. 0.	1.	610.	100.	61000.	0.

Figure C-12. Computer output run 12—peptone toxicity, 10.0 gm/l peptone.

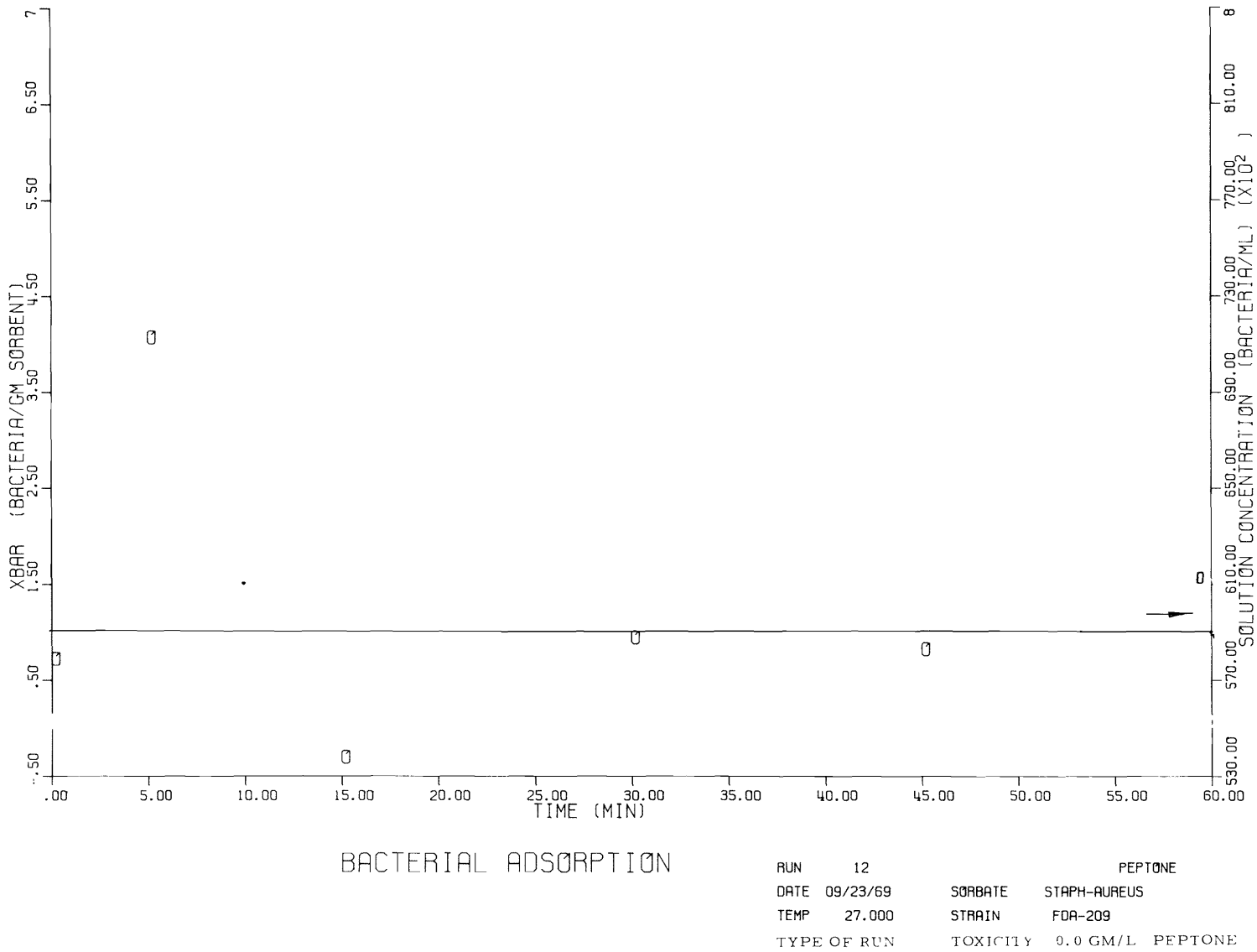


Figure C-13. Graphical output run 12—peptone toxicity, 10.0 gm/l peptone.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 09/23/69
HOUR 1500 HRS
RUN 13
TYPE OF RUN TOXICITY

SORBATE STAPH-AUREUS FDA-209 PEPTONE 30.000GM/L
SOL. VOL. 2000.0 ML
INITIAL CONC (SPECT READ) 20000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	1.	1.0	910. 0.	1.	455.	100.	45500.	0.
5.0	1.	1.0	445. 0.	1.	445.	100.	44500.	0.
15.0	1.	1.0	535. 0.	1.	535.	100.	53500.	0.
30.0	1.	1.0	510. 0.	1.	510.	100.	51000.	0.
45.0	1.	1.0	580. 0.	1.	580.	100.	58000.	0.
60.0	1.	1.0	460. 0.	1.	460.	100.	46000.	0.

Figure C-14. Computer output run 13—peptone toxicity, 30.0 gm/l peptone.

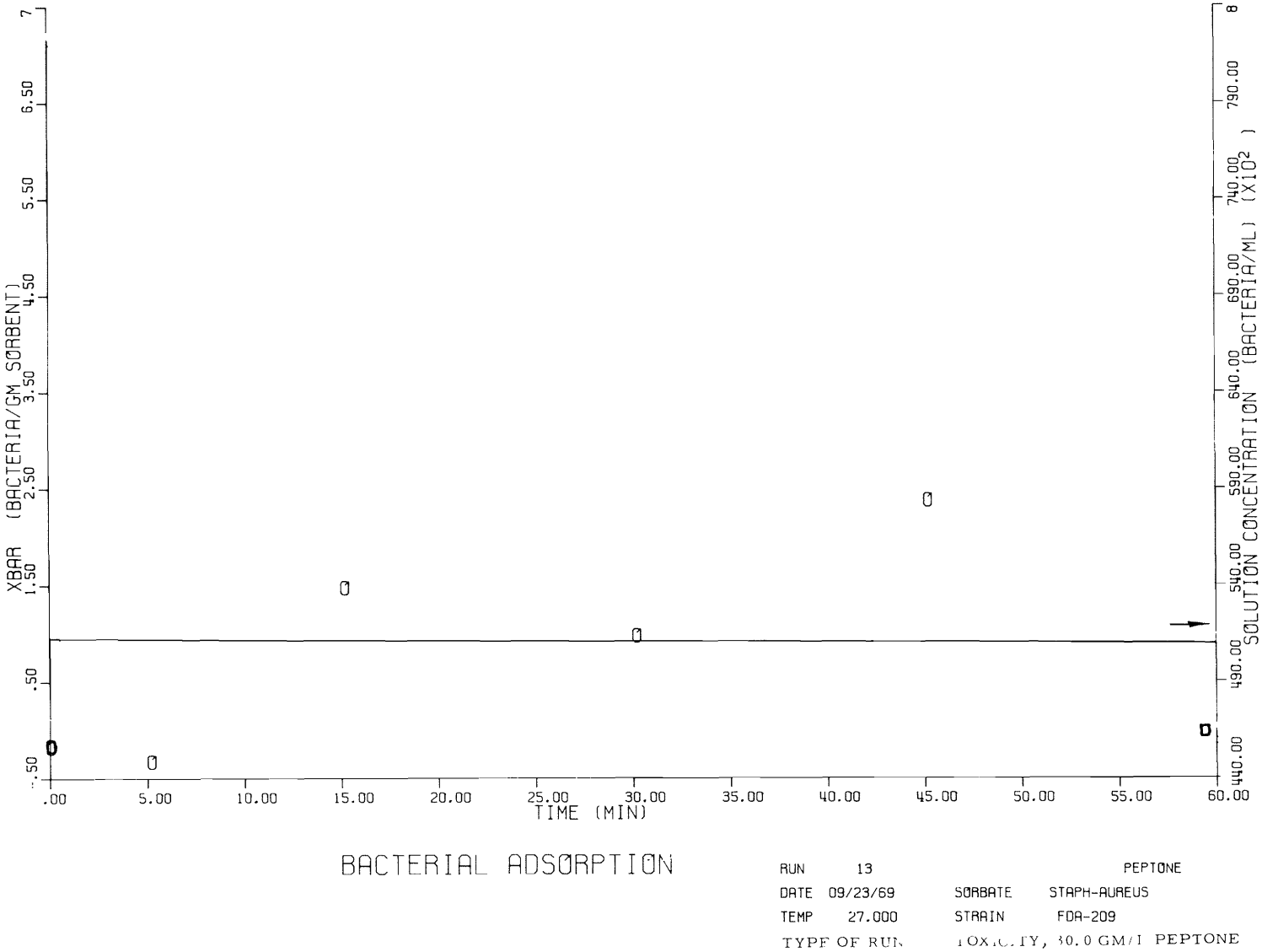


Figure C-15. Graphical output run 13—peptone toxicity, 30.0 gm/l peptone.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 09/25/69
HOUR 1500 HRS
RUN 17
TYPE OF RUN TOXICITY

SORBATE STAPH-AUREUS
FDA-209
SORBENT SODIUM CHLORIDE
40.00GM/L
INITIAL CONC (SPECT READ) 20000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 2000.0 ML
SORBENT WT. (OD)100.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	1.	1.0	210. 0.	1.	210.	100.	14700.	0.
5.0	1.	1.0	160. 0.	1.	160.	100.	16000.	0.
15.0	1.	1.0	150. 0.	1.	150.	100.	15000.	0.
30.0	1.	1.0	90. 0.	1.	90.	100.	9000.	0.
45.0	1.	1.0	130. 0.	1.	130.	100.	13000.	0.
60.0	1.	1.0	130. 0.	1.	130.	100.	13000.	0.

Figure C-16. Computer output run 17—sodium chloride toxicity, 40.0 gm/l sodium chloride.

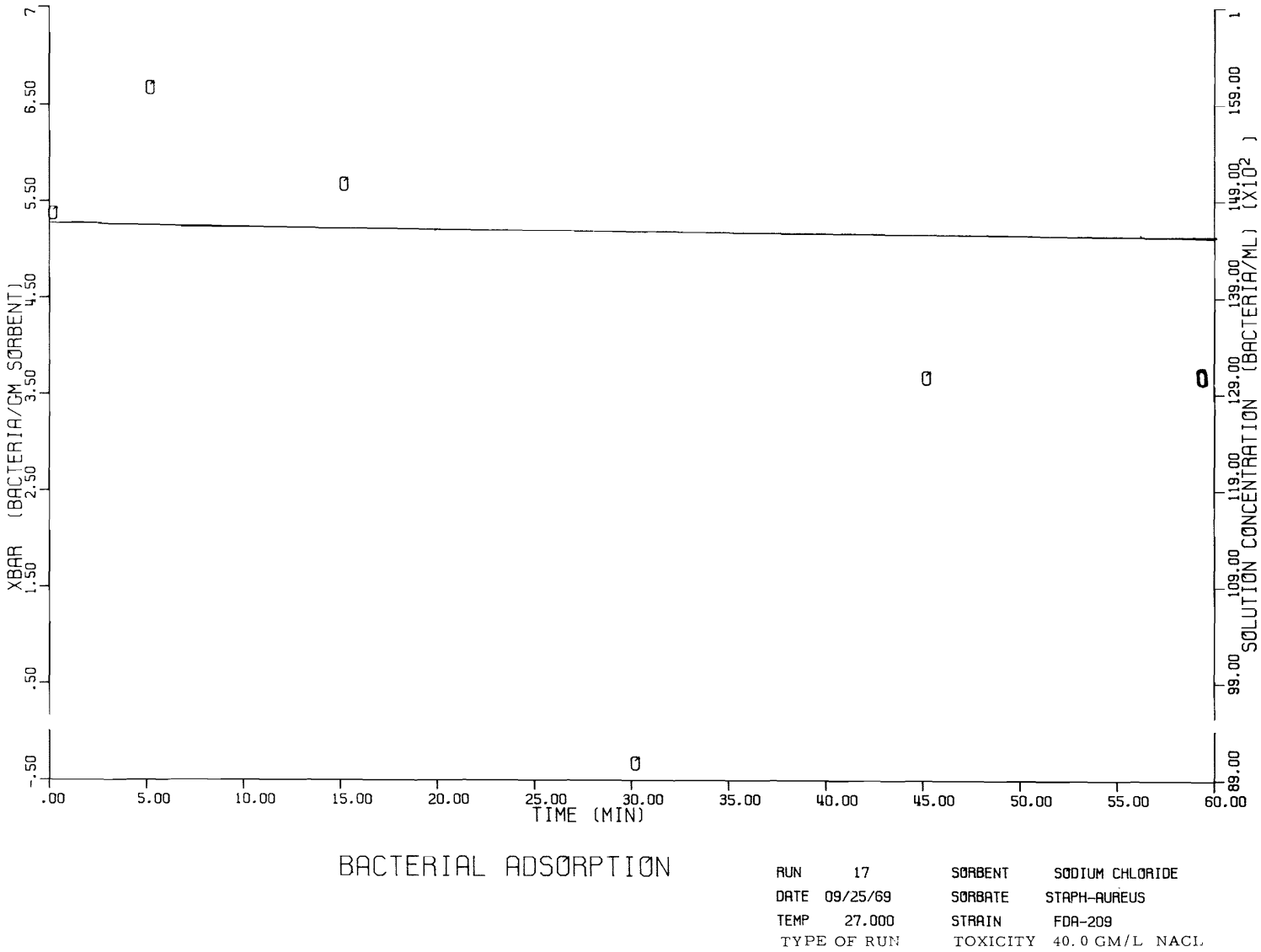


Figure C-17. Graphical output run 17—sodium chloride toxicity, 40.0 gm/l sodium chloride.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 03/02/70
HOUR 1500 HRS
RUN 25
TYPE OF RUN TOXICITY

SORBATE STAPH-AUREUS FDA-209 150.0 GM/L NACL

SOL. VOL. 200.0 ML

INITIAL CONC (SPECT READ) 100000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	110. 0.	1.	110.	1000000.	110000000.	0.
5.0	3.	1.0	85. 0.	1.	85.	1000000.	85000000.	0.
15.0	3.	1.0	70. 0.	1.	70.	1000000.	70000000.	0.
30.0	3.	1.0	45. 0.	1.	45.	1000000.	45000000.	0.
45.0	3.	1.0	60. 0.	1.	60.	1000000.	60000000.	0.
60.0	3.	1.0	50. 0.	1.	50.	1000000.	50000000.	0.

Figure C-18. Computer output run 25—sodium chloride toxicity, 150.0 gm/l sodium chloride.

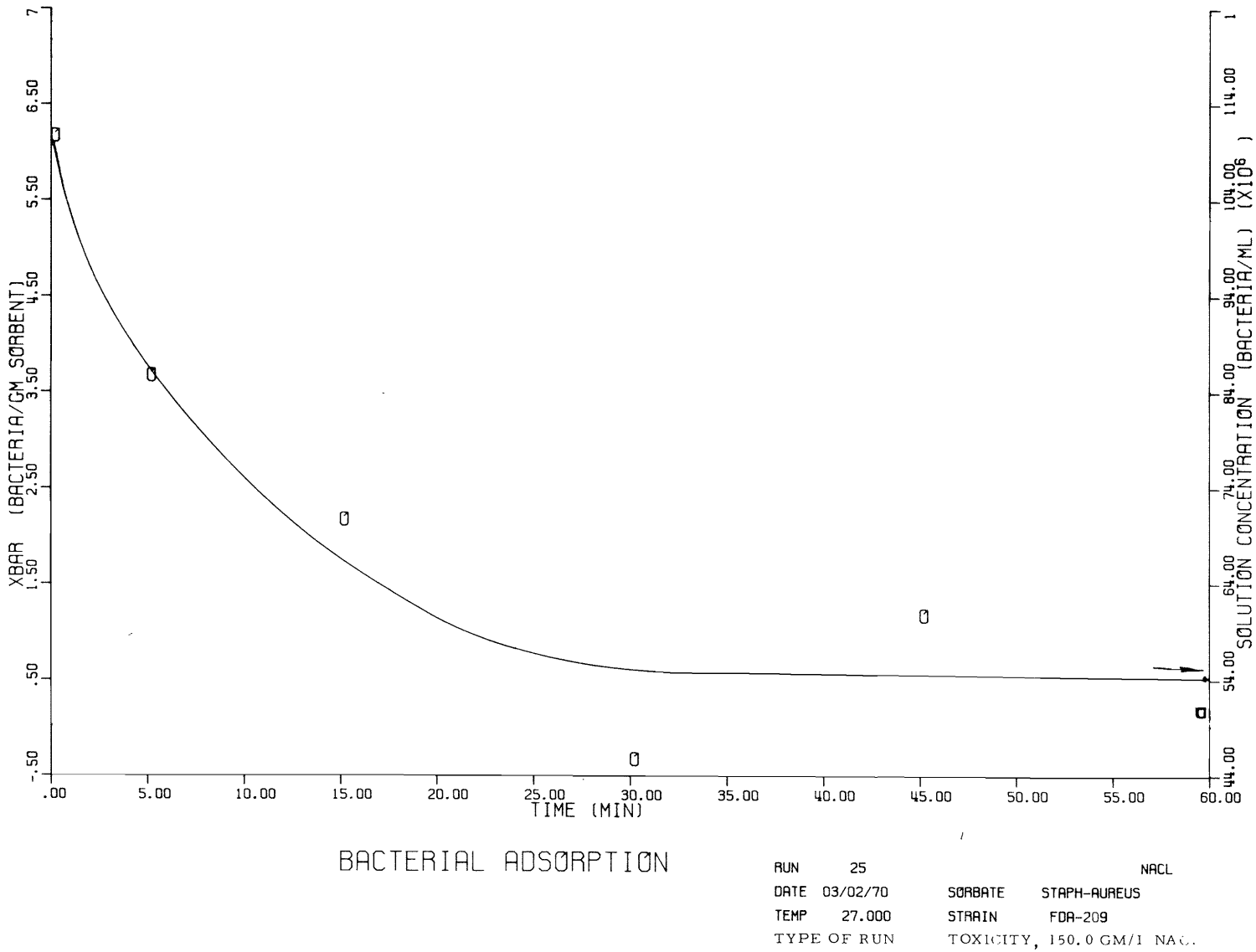


Figure C-19. Graphical output run 25—sodium chloride toxicity, 150.0 gm/l sodium chloride.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 12/17/69
HOUR 1530 HRS
RUN 23
TYPE OF RUN TOXICITY

SORBATE STAPH-AUREUS FDA-209
200.0 GM/L NACL

SOL. VOL. 1700.0 ML

INITIAL CONC (SPECT READ) 50000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	75. 0.	1.	75.	1000000.	74999999.	0.
5.0	3.	1.0	60. 0.	1.	60.	1000000.	60000000.	0.
15.0	3.	1.0	40. 0.	1.	40.	1000000.	40000000.	0.
30.0	3.	1.0	35. 0.	1.	35.	1000000.	35000000.	0.
45.0	3.	1.0	45. 0.	1.	45.	1000000.	45000000.	0.
60.0	3.	1.0	35. 0.	1.	35.	1000000.	35000000.	0.

Figure C-20. Computer output run 23—sodium chloride toxicity, 200.0 gm/l sodium chloride.

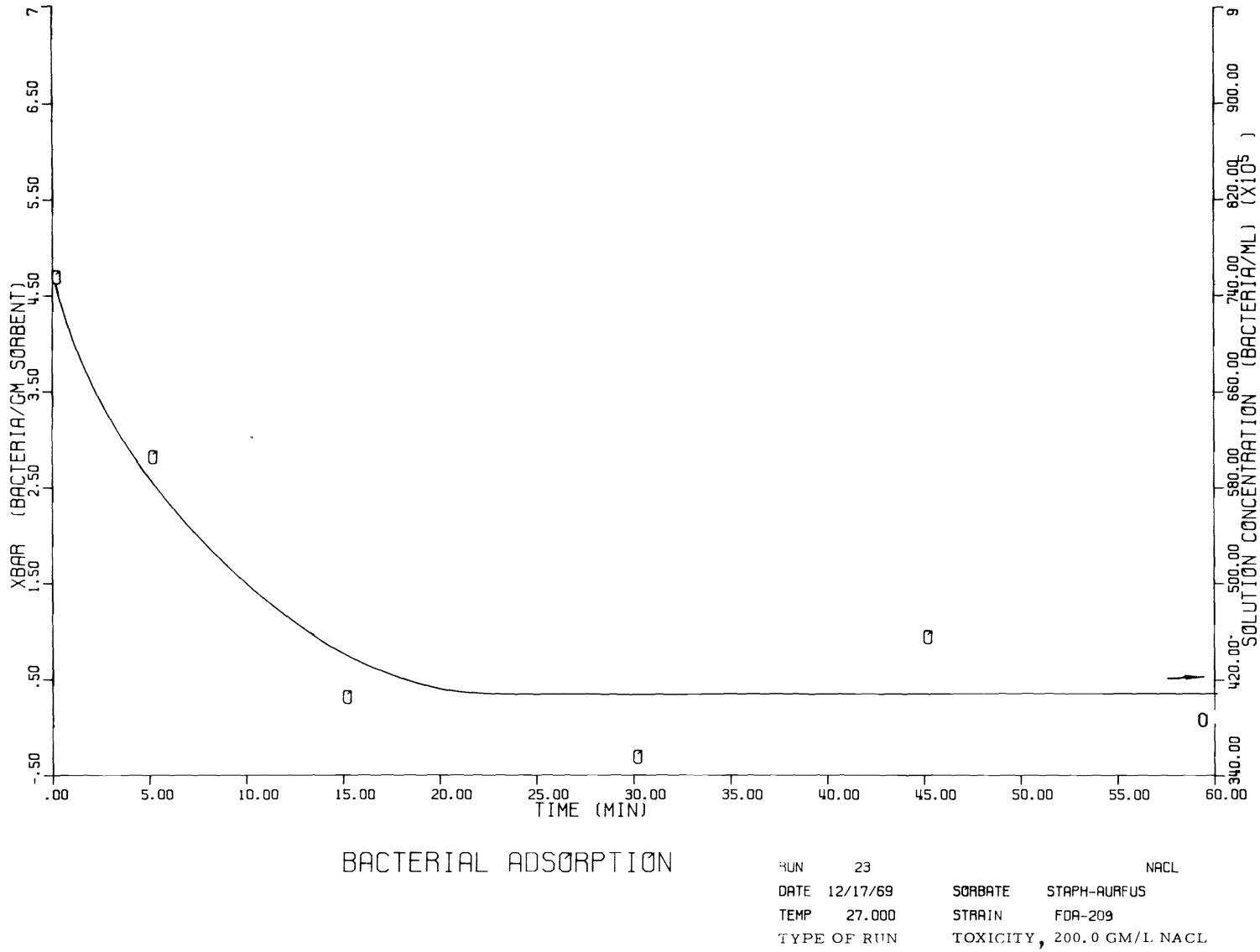


Figure C-21. Graphical output run 23—sodium chloride toxicity, 200.0 gm/l sodium chloride.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 10/24/69
HOUR 1500 HRS
RUN 1
TYPE OF RUN 0.0GLS/L

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL
MENDON SILT LOAM
INITIAL CONC (SPECT READ) 200000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 1935.0 ML
SORBENT WT. (OD) 10.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML FA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	180. 0.	1.	180.	1000000.	161395348.	0.
5.0	3.	1.0	160. 0.	1.	160.	1000000.	160000000.	267999718.
15.0	3.	1.0	130. 0.	1.	130.	1000000.	130000000.	606699680.
30.0	3.	1.0	100. 0.	1.	100.	1000000.	100000000.	1186299803.
45.0	3.	1.0	135. 0.	1.	135.	1000000.	135000000.	510449840.
60.0	3.	1.0	80. 0.	1.	80.	1000000.	80000000.	157194997 76.

Figure C-22. Computer output run 1—sodium lauryl sulfate competitive level test, 0.0 gm/l SLS.

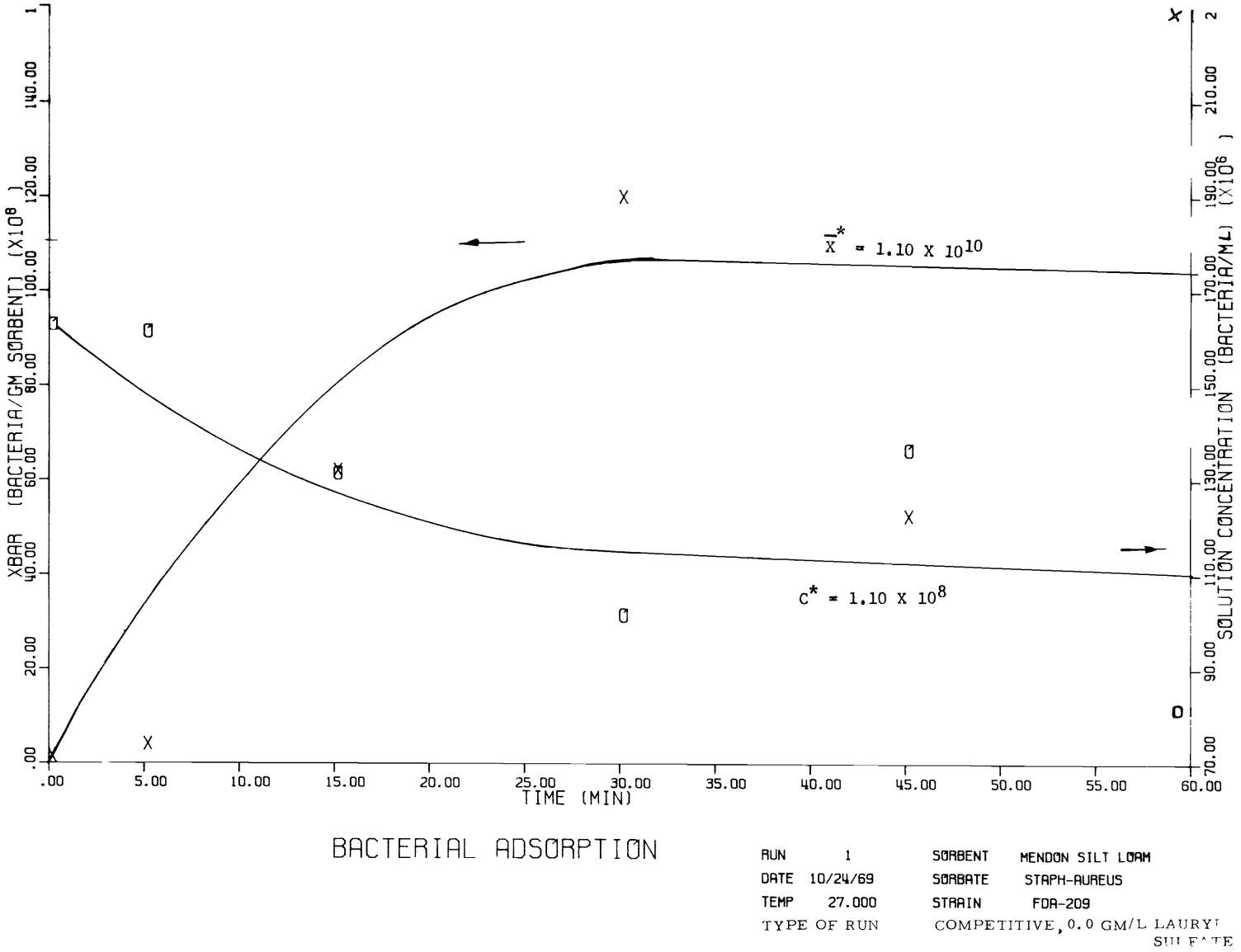


Figure C-23. Graphical output run 1—sodium lauryl sulfate competitive level test, 0.0 gm/l SLS.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 10/24/69
HOUR 1500 HRS
RUN 2
TYPE OF RUN .05SLS#/L

SORBATE STAPH-AUREUS FDA-209
SOL. VOL. 1935.0 ML
SORBENT WT. (DRY) 10.0 GM
SORBENT SOIL
MENDON SILT LOAM
INITIAL CONC (SPECT READ) 200000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	180. 0.	1.	180.	1000000.	161395348.	0.
5.0	3.	1.0	140. 0.	1.	140.	1000000.	140000000.	41359398872.
15.0	3.	1.0	105. 0.	1.	105.	1000000.	105000000.	10901499520.
30.0	3.	1.0	125. 0.	1.	125.	1000000.	125000000.	7037499648.
45.0	3.	1.0	115. 0.	1.	115.	1000000.	115000000.	8968499712.
60.0	3.	1.0	100. 0.	1.	100.	1000000.	100000000.	11663499776.

Figure C-24. Computer output run 2—sodium lauryl sulfate competitive level test, 0.05 gm/l SLS.

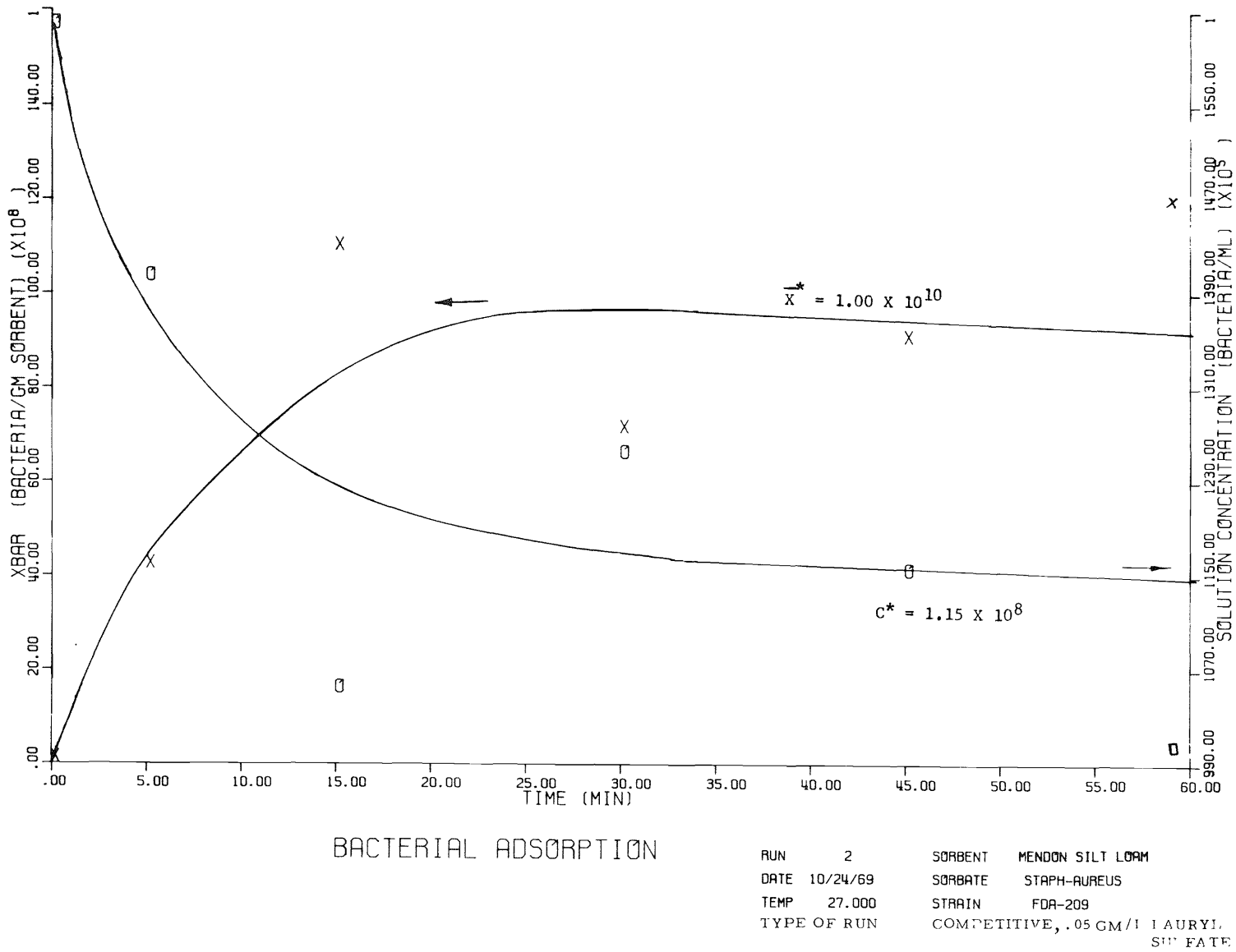


Figure C-25. Graphical output run 2—sodium lauryl sulfate competitive level test, 0.05 gm/l SLS.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 11/10/69
HOUR 1500 HRS
RUN 7
TYPE OF RUN 0.00PEP/L

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL
MENDON SILT LOAM
INITIAL CONC (SPECT READ) 100000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 1925.0 ML
SORBENT WT. (OD) 10.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	115. 0.	1.	115.	1000000.	103651947.	0.
5.0	3.	1.0	65. 0.	1.	65.	1000000.	65000000.	7319999744.
15.0	3.	1.0	75. 0.	1.	75.	1000000.	75000000.	5396999680.
30.0	3.	1.0	70. 0.	1.	70.	1000000.	70000000.	6357999744.
45.0	3.	1.0	65. 0.	1.	65.	1000000.	65000000.	7318499584.
60.0	3.	1.0	70. 0.	1.	70.	1000000.	70000000.	6358499648.

Figure C-26. Computer output run 7—peptone competitive level test, 0.00 gm/l peptone.

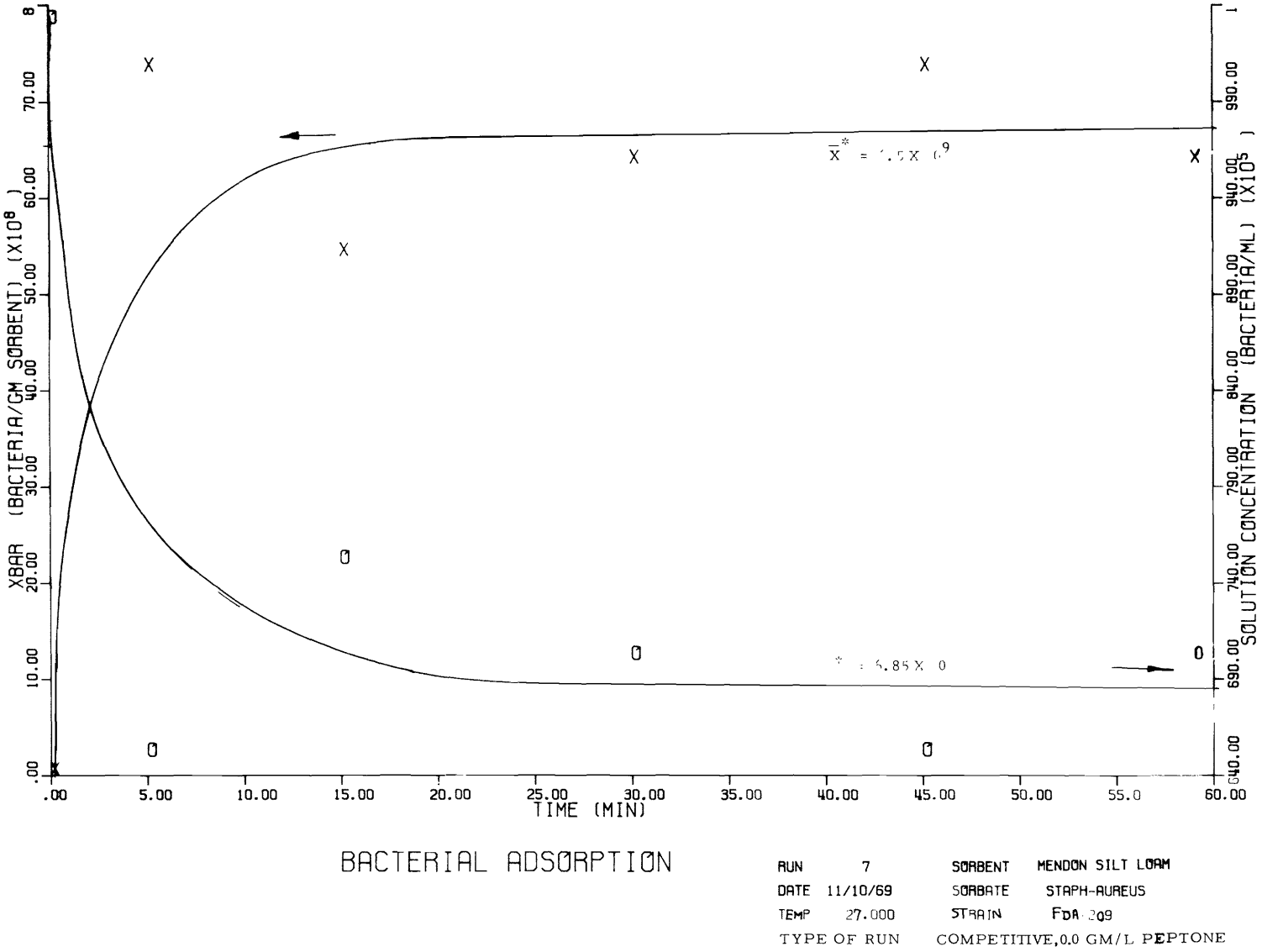


Figure C-27. Graphical output run 7—peptone competitive level test, 0.00 gm/l peptone.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 11/25/69
HOUR 1500 HRS
RUN 30
TYPE OF RUN 3.5GPP/L

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL MENDON SILT LOAM
INITIAL CONC (SPECT READ) 30000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 1700.0 ML
SORBENT WT. (OD) 10.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	2.	.1	275. 0.	1.	275.	100000.	27500000.	0.
5.0	2.	.1	215. 0.	1.	215.	100000.	21500000.	1019399936.
15.0	2.	.1	210. 0.	1.	210.	100000.	21000000.	1104299936.
30.0	2.	.1	205. 0.	1.	205.	100000.	20500000.	1189199904.
45.0	2.	.1	230. 0.	1.	230.	100000.	23000000.	765149920.
60.0	2.	.1	225. 0.	1.	225.	100000.	22500000.	849899928.

Figure C-28. Computer output run 30—peptone competitive level test, 3.5 gm/l peptone.

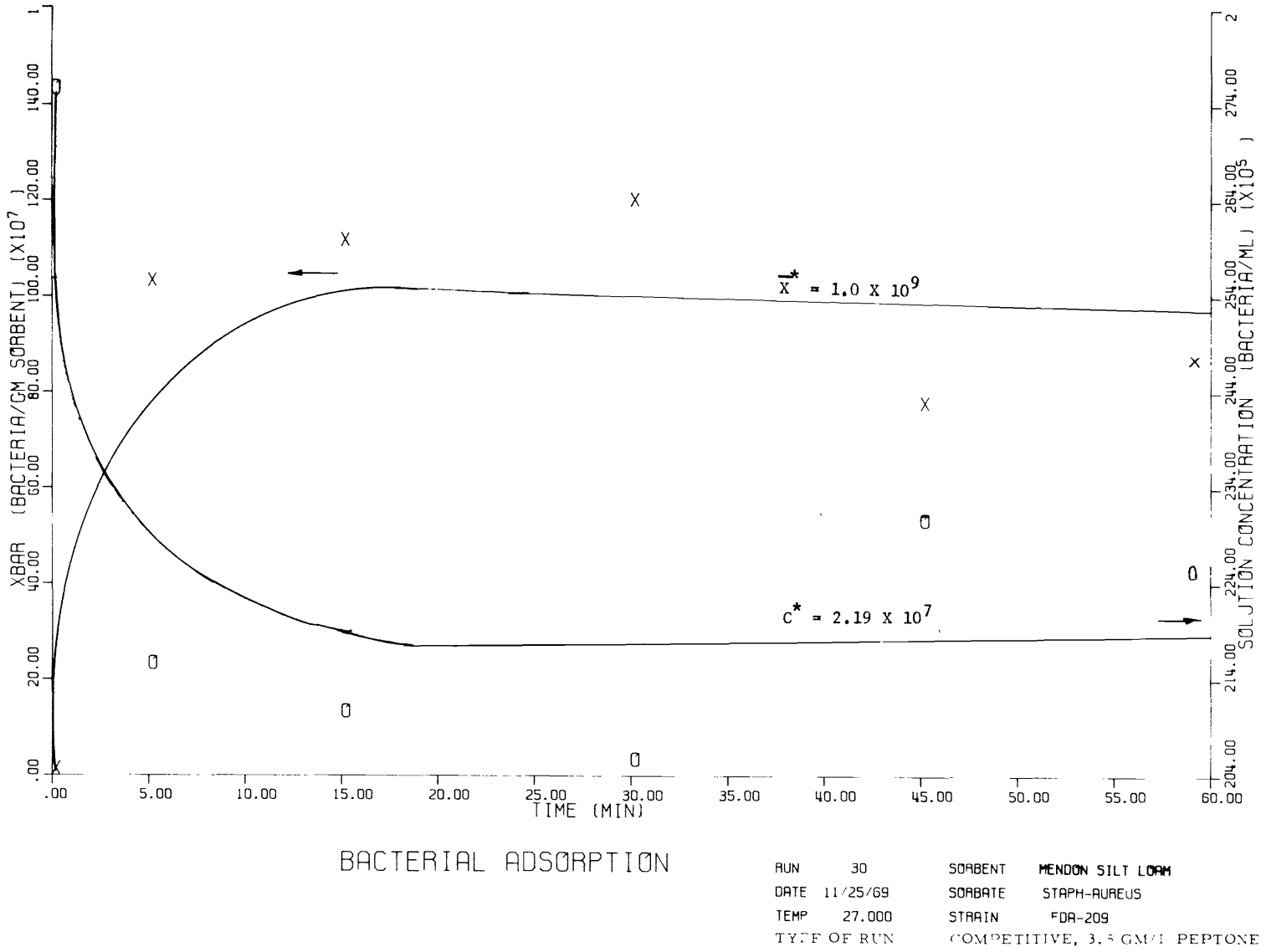


Figure C-29. Graphical output run 30—peptone competitive level test, 3.5 gm/l peptone.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 11/10/69
HOUR 1500 HRS
RUN 11
TYPE OF RUN 30GPEP/L

SORBATE STAPH-AUREUS
FDA-209
SORBENT SOIL
MENDON SILT LOAM
INITIAL CONC (SPECT READ) 100000000. BUGS/ML
TEMP 27.C DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 1925.0 ML
SORBENT WT. (OD) 10.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	90. 0.	1.	90.	1000000.	80649350.	0.
5.0	3.	1.0	75. 0.	1.	75.	1000000.	75000000.	108599984 0.
15.0	3.	1.0	80. 0.	1.	80.	1000000.	80000000.	124499782.
30.0	3.	1.0	75. 0.	1.	75.	1000000.	75000000.	108549973 2
45.0	3.	1.0	75. 0.	1.	75.	1000000.	75000000.	108549977 6
60.0	3.	1.0	80. 0.	1.	80.	1000000.	80000000.	125499884

Figure C-30. Computer output run 11—peptone competitive level test, 30.0 gm/l peptone.

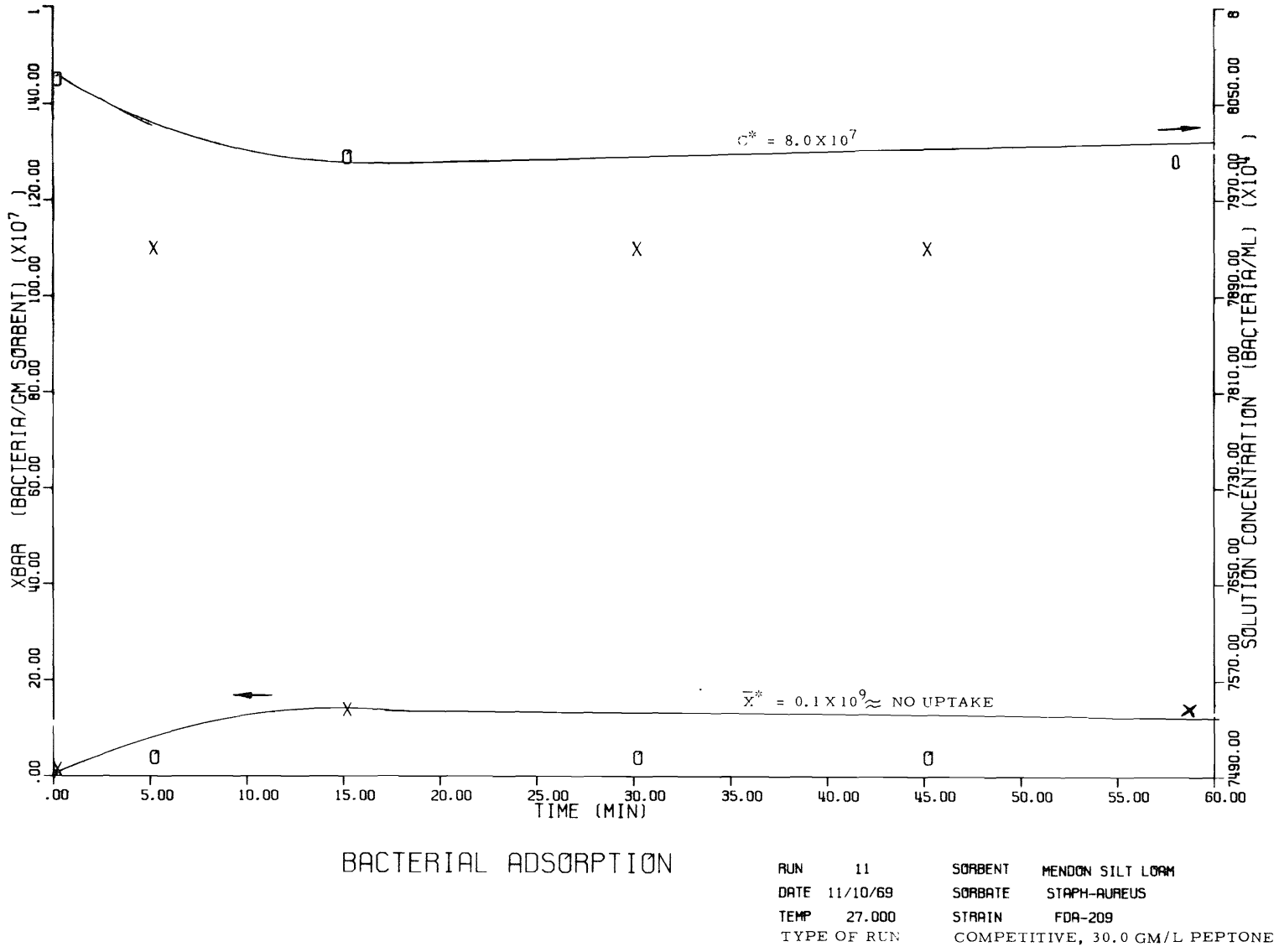


Figure C-31. Graphical output run 11—peptone competitive level test, 30.0 gm/l peptone.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 10/18/69
HOUR 1500 HRS
RUN 13
TYPE OF RUN 0.0 GM/L NACL

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL MENDON SILT LOAM
INITIAL CONC (SPECT READ) 100000000. PUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 1820.0 ML
SORBENT WT. (OD) 10.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	90. 0.	1.	90.	1000000.	86624999.	0.
5.0	3.	1.0	55. 0.	1.	55.	1000000.	55600000.	4916499712.
15.0	3.	1.0	70. 0.	1.	70.	1000000.	70000000.	2039499904.
30.0	3.	1.0	50. 0.	1.	50.	1000000.	50000000.	5873499840.
45.0	3.	1.0	40. 0.	1.	40.	1000000.	40000000.	7789499904.
60.0	3.	1.0	60. 0.	1.	60.	1000000.	60000000.	3959499872.

Figure C-32. Computer output run 13—sodium chloride competitive level test, 0.0 gm/l sodium chloride.

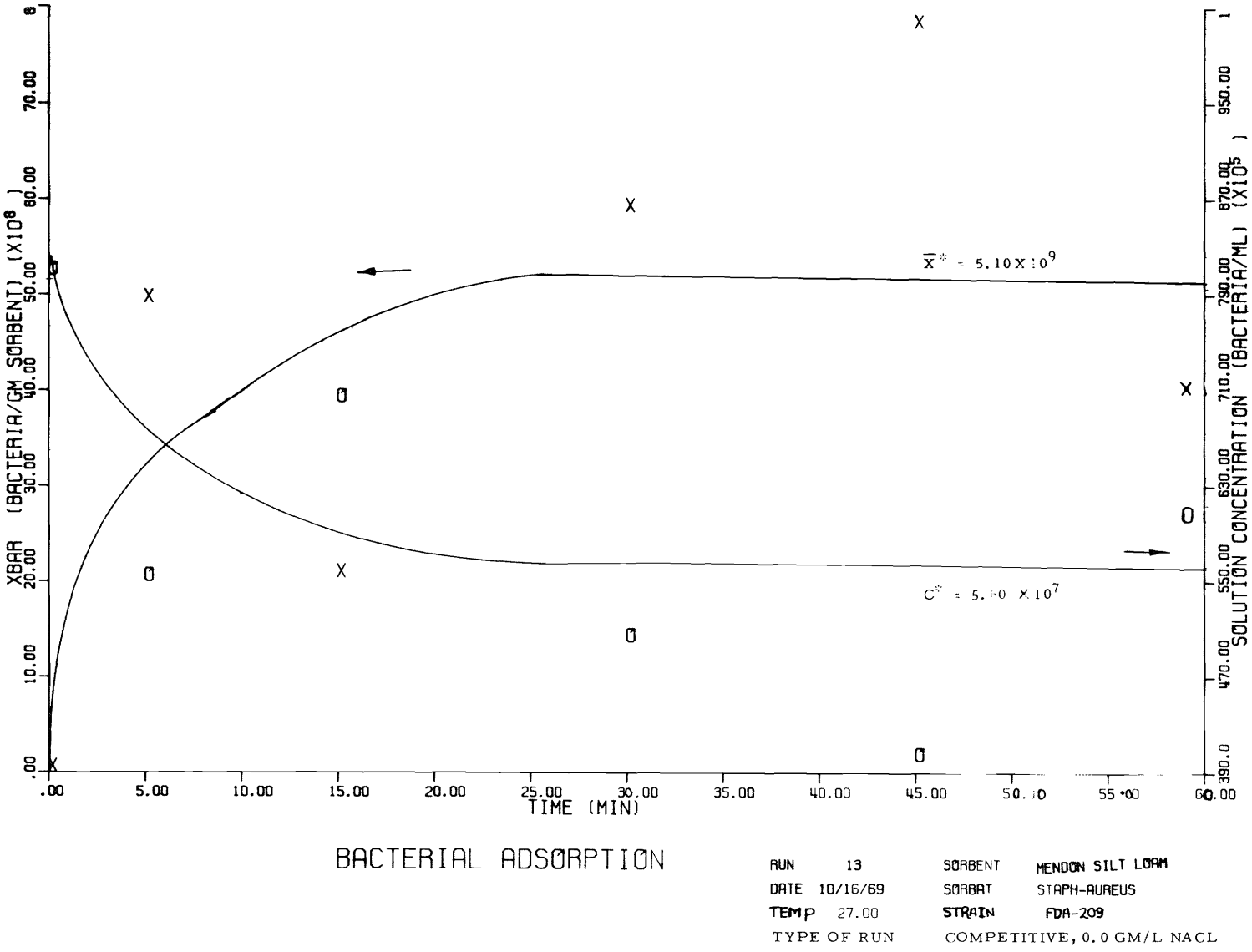


Figure C-33. Graphical output run 13—sodium chloride competitive level test, 0.0 gm/l sodium chloride.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 10/29/69
HOUR 1500 HRS
RUN 3
TYPE OF RUN 30.0 GM/L NACL

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL MENDON SILT LOAM
INITIAL CONC (SPECT READ) 125000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 1920.0 ML
SORBENT WT. (DD) 10.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	140. 0.	1.	140.	1000000.	125416566.	0.
5.0	3.	1.0	95. 0.	1.	95.	1000000.	85000000.	5835499904.
15.0	3.	1.0	90. 0.	1.	90.	1000000.	80000000.	6794499840.
30.0	3.	1.0	95. 0.	1.	95.	1000000.	85000000.	5835999808.
45.0	3.	1.0	95. 0.	1.	95.	1000000.	85000000.	5835999872.
60.0	3.	1.0	70. 0.	1.	70.	1000000.	70000000.	10623499904.

Figure C-34. Computer output run 8—sodium chloride competitive level test, 30.0 gm/l sodium chloride.

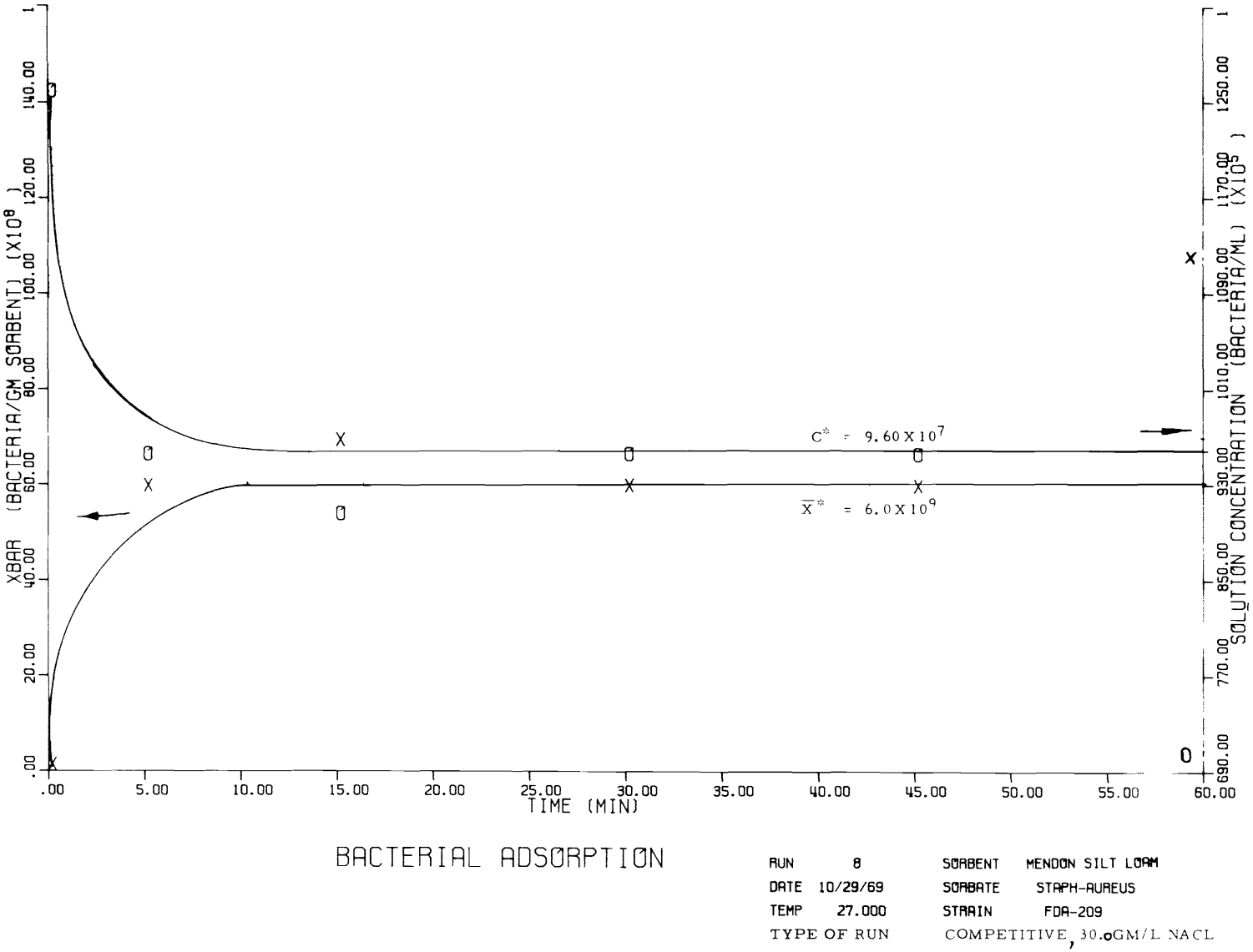


Figure C-35. Graphical output run 8—sodium chloride competitive level test, 30.0 gm/l sodium chloride.

TABLE 2 BACTERIAL ADSORPTION EXPERIMENTS - COLLECTION AND REDUCTION OF DATA

DATE 01/30/70
HOUR 1500 HRS
RUN 24
TYPE OF RUN 100.0 GM/L NACL

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL MENDON SILT LOAM
INITIAL CONC (SPECT READ) 75000000. BUGS/ML
TEMP 27.0 DEG. C.
SAMPLE VOL. 1.0 ML

SOL. VOL. 200.0 ML
SORBENT WT. (OD) 1.0 GM

ELAPSED TIME (MIN)	NO. OF DIL. OF 99 ML EA.	PIPET VOL. DEL. TO PLATE (ML)	FILTER PLATE COUNT (BUGS/PLATE)	NO. OF VALID OBS.	AVG FILTER PLATE COUNT (BUGS/PLATE)	DIL. FACT.	SOLUTION CONC. (BUGS/ML)	XBAR (BUGS/GM)
.0	3.	1.0	80. 0.	1.	80.	1000000.	68000000.	0.
5.0	3.	1.0	15. 0.	1.	15.	1000000.	15000000.	1053500064.
15.0	3.	1.0	30. 0.	1.	30.	1000000.	30000000.	7565000000.
30.0	3.	1.0	15. 0.	1.	15.	1000000.	15000000.	1052000000.
45.0	3.	1.0	20. 0.	1.	20.	1000000.	20000000.	9540000000.
60.0	3.	1.0	15. 0.	1.	15.	1000000.	15000000.	1051500064.

Figure C-36. Computer output run 24—sodium chloride competitive level test, 100.0 gm/l sodium chloride.

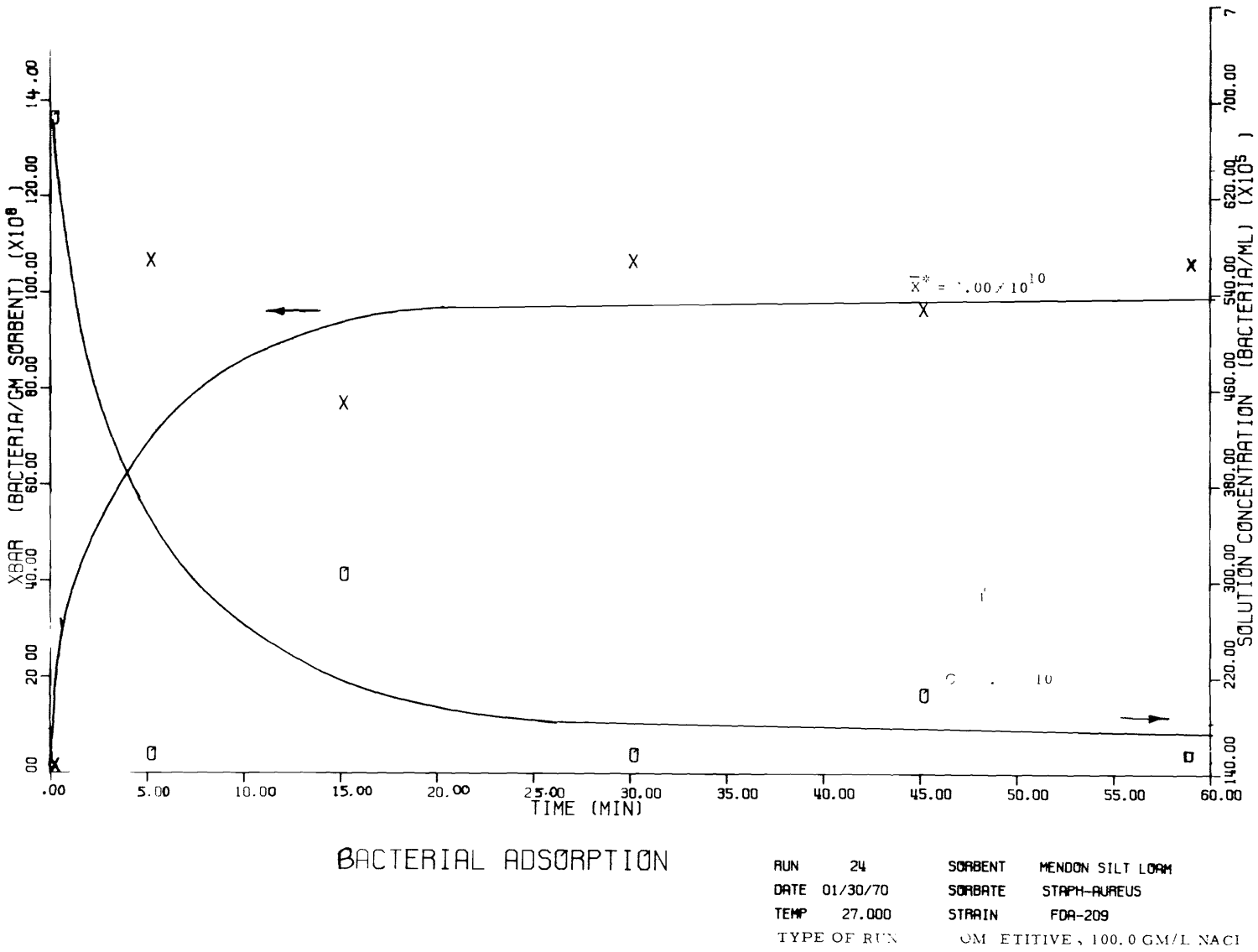


Figure C-37. Graphical output run 24—sodium chloride competitive level test, 100.0 gm/l sodium chloride.

APPENDIX D

BACTERIAL ADSORPTION ISOTHERMS (WITHOUT CHEMICAL COMPETITION)

Bacto-Peptone 0 gm/l
Sodium Chloride 0 gm/l
Sodium Lauryl Sulfate 0 gm/l

Bacterial adsorption isotherms (Langmuir and linear) in the absence of chemical competition are shown in this appendix for activated charcoal, kaolinite clay, Mendon silt loam and silica sand, all with *S. aureus* as the sorbate. These isotherms were obtained at 10C, 20C, 27C, and 37C. The output in the tables shows the isotherm parameters such as α (the equilibrium constant), X_m (the maximum adsorption capacity of adsorbent), and R^2 (the regression coefficient). These results are summarized in the text, in Table 2.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 12/15/69
RUNS 1 TO 7

SORBATE STAPH-AUREUS FDA-209
SORBENT CHARCOAL FILTRASORB-400
TEMP 10.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R =	.992
RSQ =	.813
YINTERCEPT = 1/(ALPHA*XMAX) =	.164804-02
SLOPE OF BEST FIT =	.221415-09
ALPHA =	.134350-06
XMAX =	.451640+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	(1/C**XBAR*)
1	12/15/69	.41000+06	.15000+09	.27333-02
2	12/15/69	.22500+07	.11400+10	.19737-02
3	12/20/69	.17300+08	.30000+10	.57667-02
4	12/20/69	.90000+07	.30000+10	.30000-02
5	12/25/69	.68500+07	.25000+10	.27400-02
6	12/25/69	.11500+09	.30000+10	.38333-02
7	12/30/69	.11000+09	.25000+10	.44000-02

Figure D-1. Analysis of equilibrium data, runs 1-7—*S. aureus* and activated charcoal, 10C.

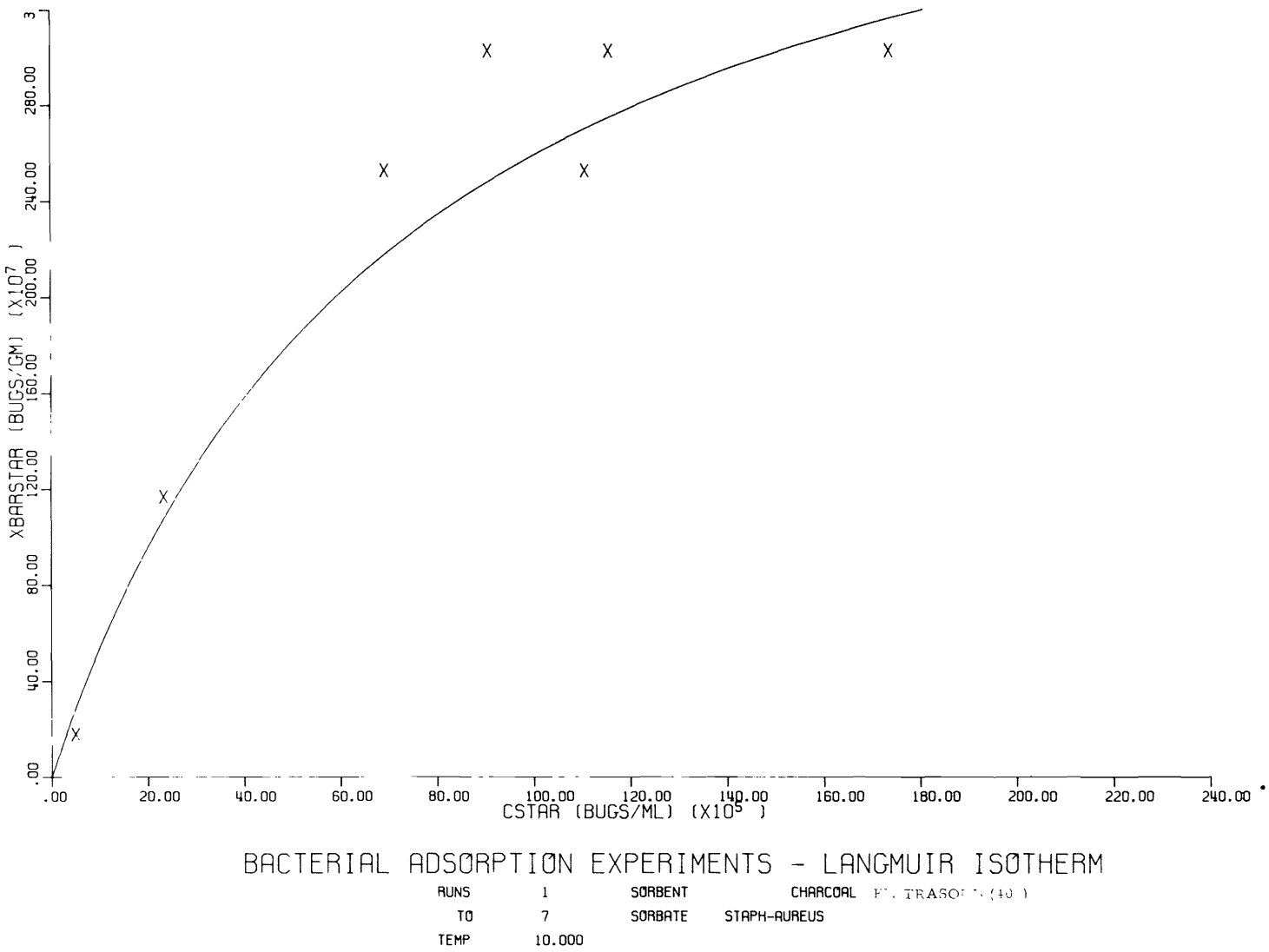


Figure D-2. Langmuir isotherm, runs 1-7—*S. aureus* and activated charcoal, 10C.

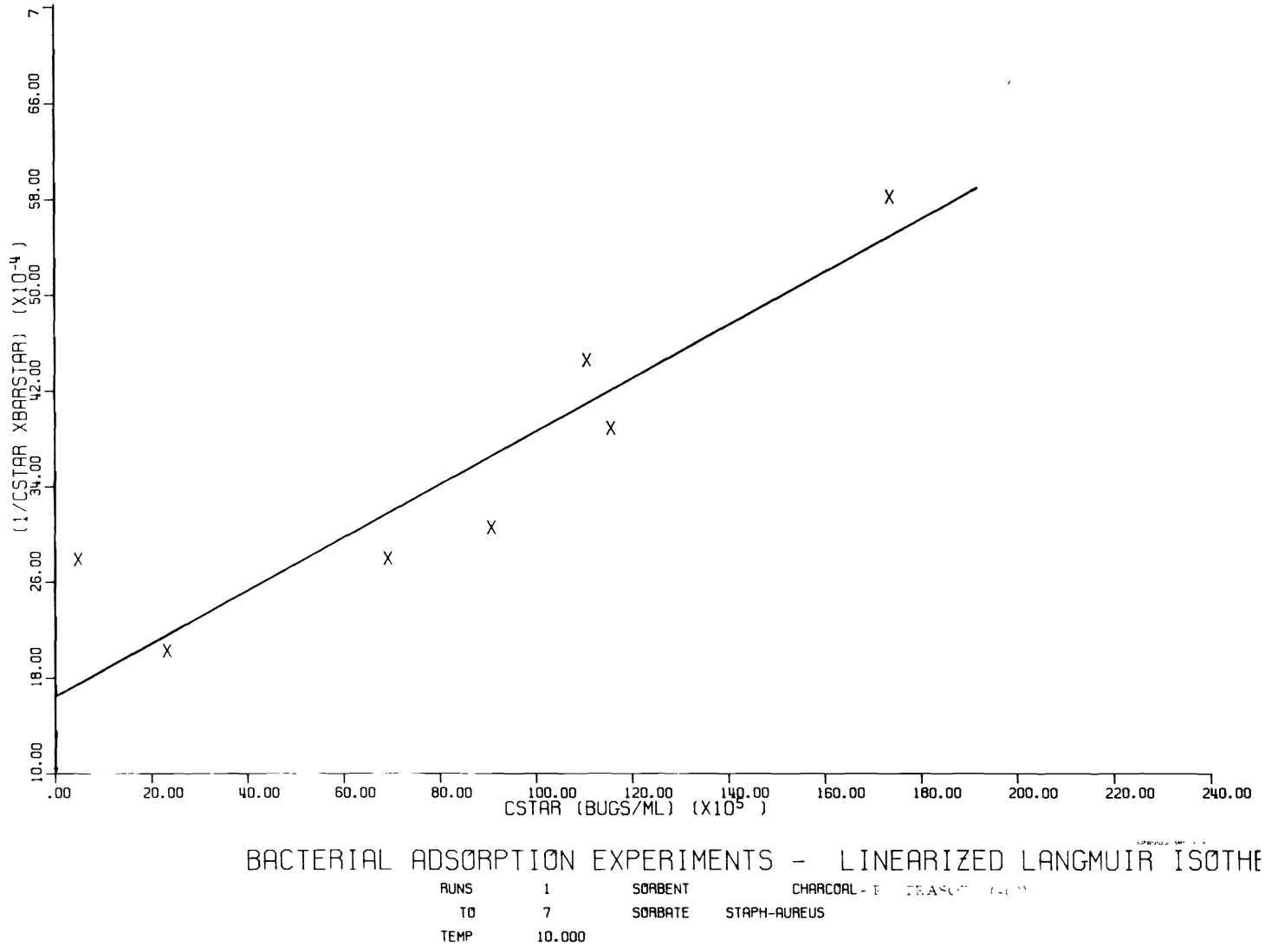


Figure D-3. Linearized Langmuir isotherm, runs 1-7—*S. aureus* and activated charcoal, 10C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 02/05/69
RUNS 1 TO 5

SORBATE STAPH-AUREUS
FDA-209
SORBENT CHARCOAL
FILTRASORB-400
TEMP 20.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R =	.897
RSQ =	.805
YINTERCEPT = 1/(ALPHA*XMAX) =	.837517-03
SLOPE OF BEST FIT =	.152490-09
ALPHA =	.186018-06
XMAX =	.615422+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
1	02/05/69	.62000+07	.40000+10	.15500-02
2	02/05/69	.45000+07	.22000+10	.20455-02
3	02/05/69	.12800+08	.50000+10	.25600-02
4	02/05/69	.10500+08	.38000+10	.27632-02
5	02/05/69	.16300+08	.45000+10	.36222-02

Figure D-4. Analysis of equilibrium data, run 1-11—*S. aureus* and activated charcoal, 20C.

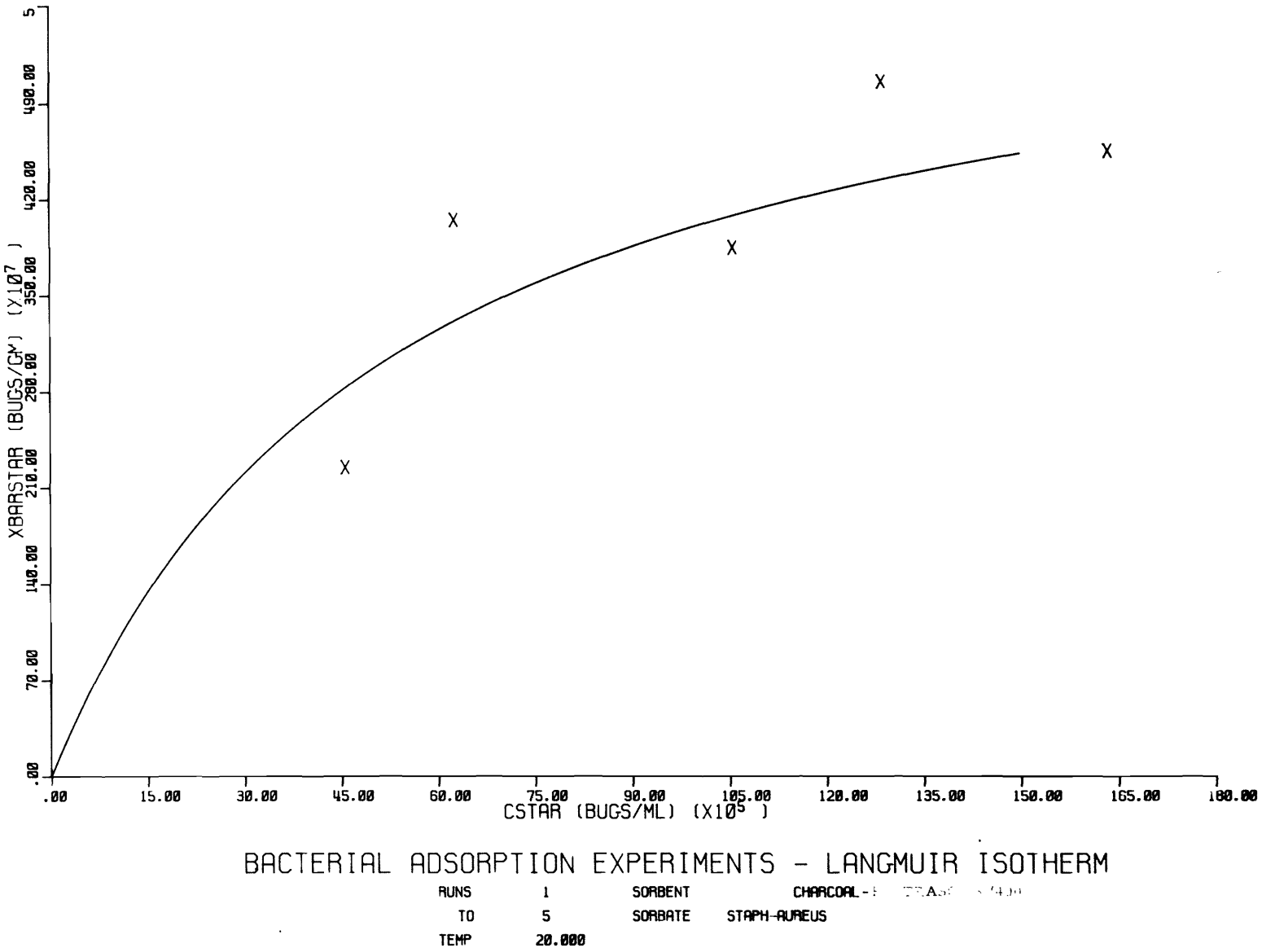


Figure D-5. Langmuir isotherm, runs 1-11—*S. aureus* and activated charcoal, 20C.

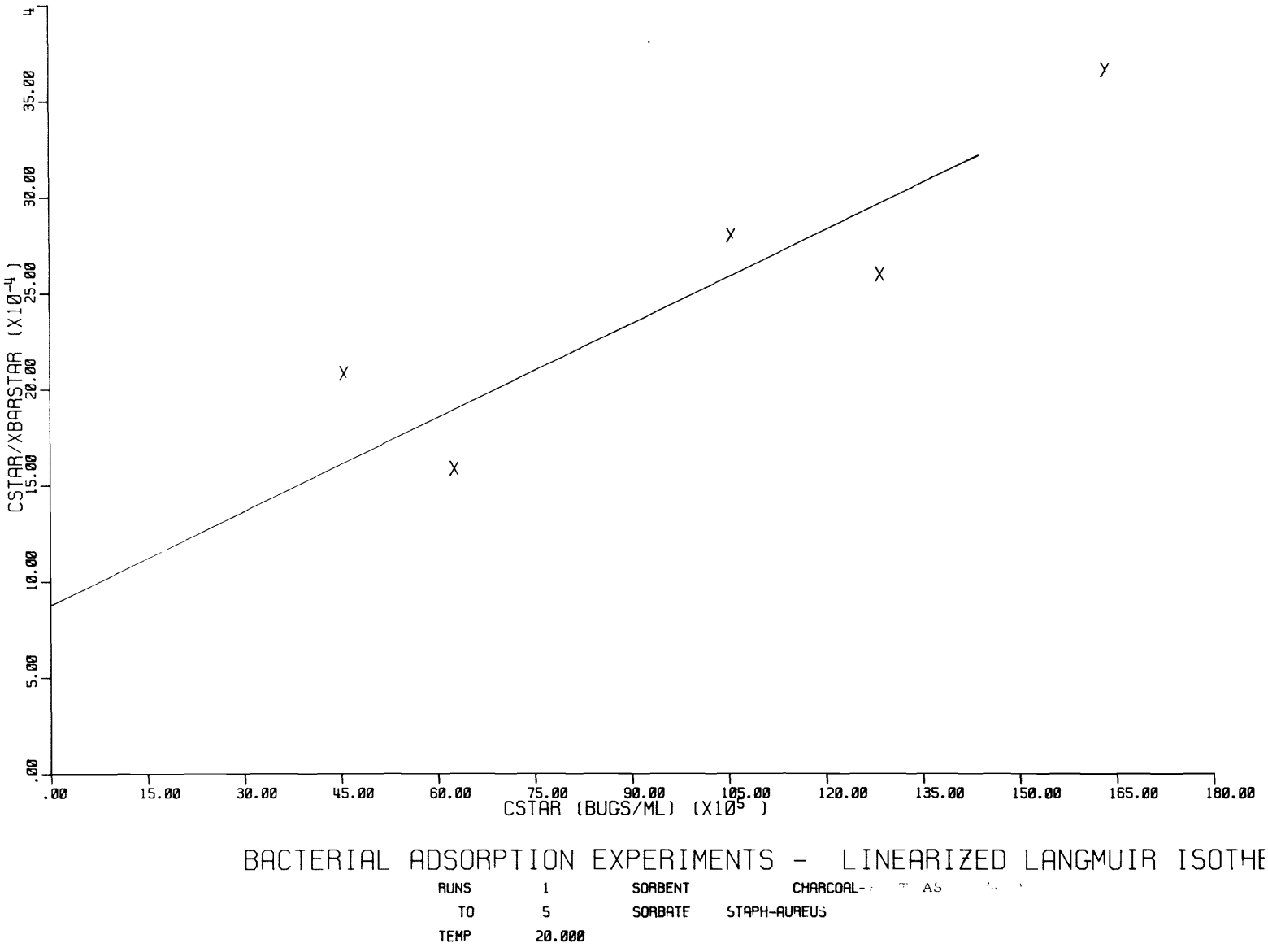


Figure D-6. Linearized Langmuir isotherm, runs 1-11—*S. aureus* and activated charcoal, 20C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 12/29/69
RUNS 1 TO 11

SORBATE STAPH-AUREUS FDA-209
SORBENT CHARCOAL FILTRANSORB-400
TEMP 27.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .913
RSQ = .834
YINTERCEPT = 1/(ALPHA*XMAX) = .191396-03
SLOPE OF BEST FIT = .270580-09
ALPHA = .104799-05
XMAX = .498553+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	(1/C**XBAR*)
1	12/29/69	.20000+08	.40000+10	.50000-02
2	12/29/69	.11300+08	.40000+10	.28250-02
3	12/30/69	.12000+08	.57000+10	.21053-02
4	12/30/69	.88000+07	.55000+10	.16000-02
5	01/25/69	.30000+07	.32000+10	.93750-03
6	01/25/69	.25000+07	.20000+10	.12500-02
7	01/27/69	.50000+06	.70000+09	.71429-03
8	01/27/69	.90000+07	.55000+10	.16364-02
9	01/28/69	.61000+07	.45000+10	.13556-02
10	01/28/69	.16000+08	.62000+10	.25806-02
11	01/29/69	.12900+08	.50000+10	.25800-02

Figure D-7. Analysis of equilibrium data, runs 1-11—*S. aureus* and activated charcoal, 27C.

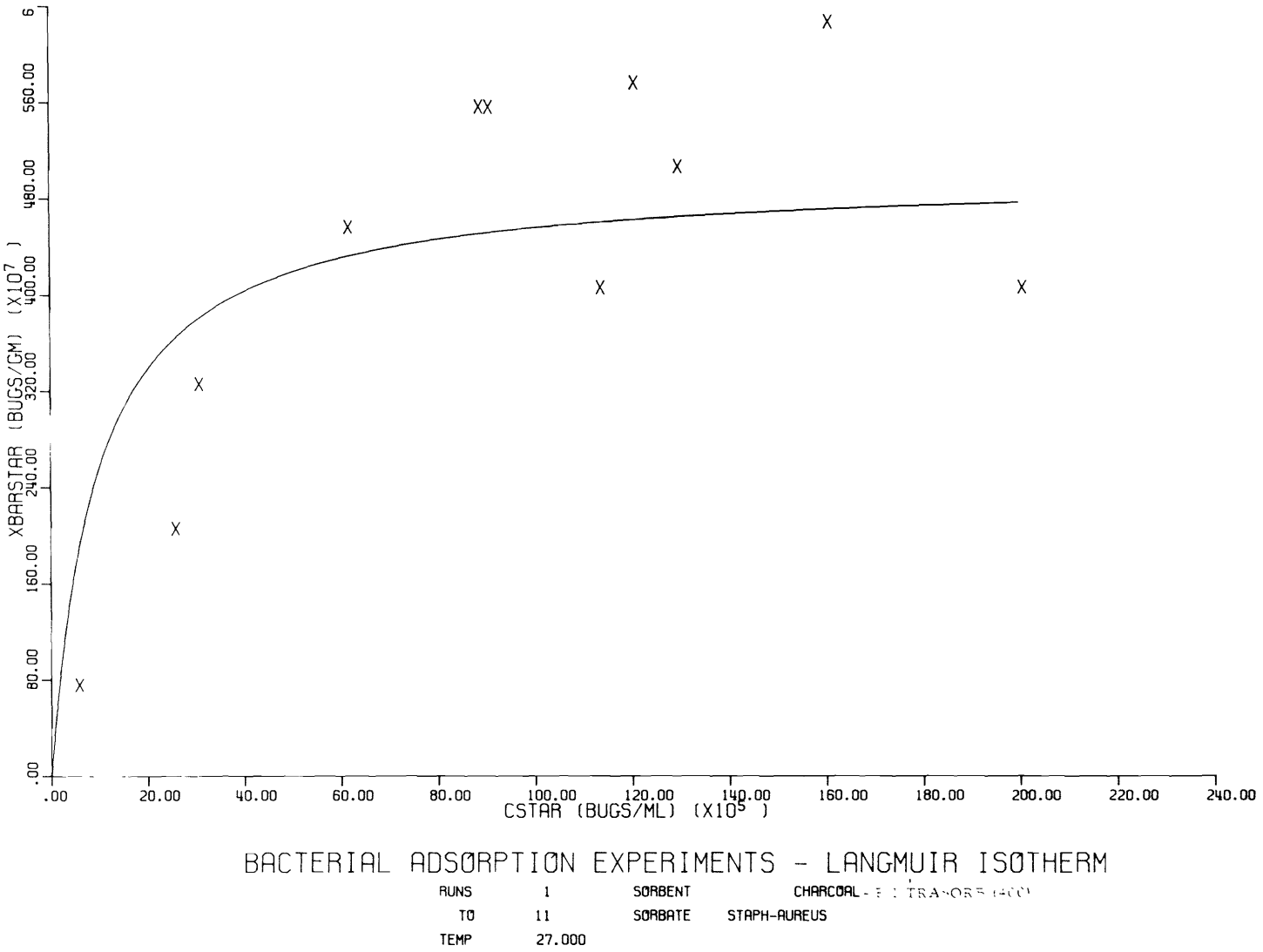


Figure D-8. Langmuir isotherm, runs 1-11—*S. aureus* and activated charcoal, 27C.

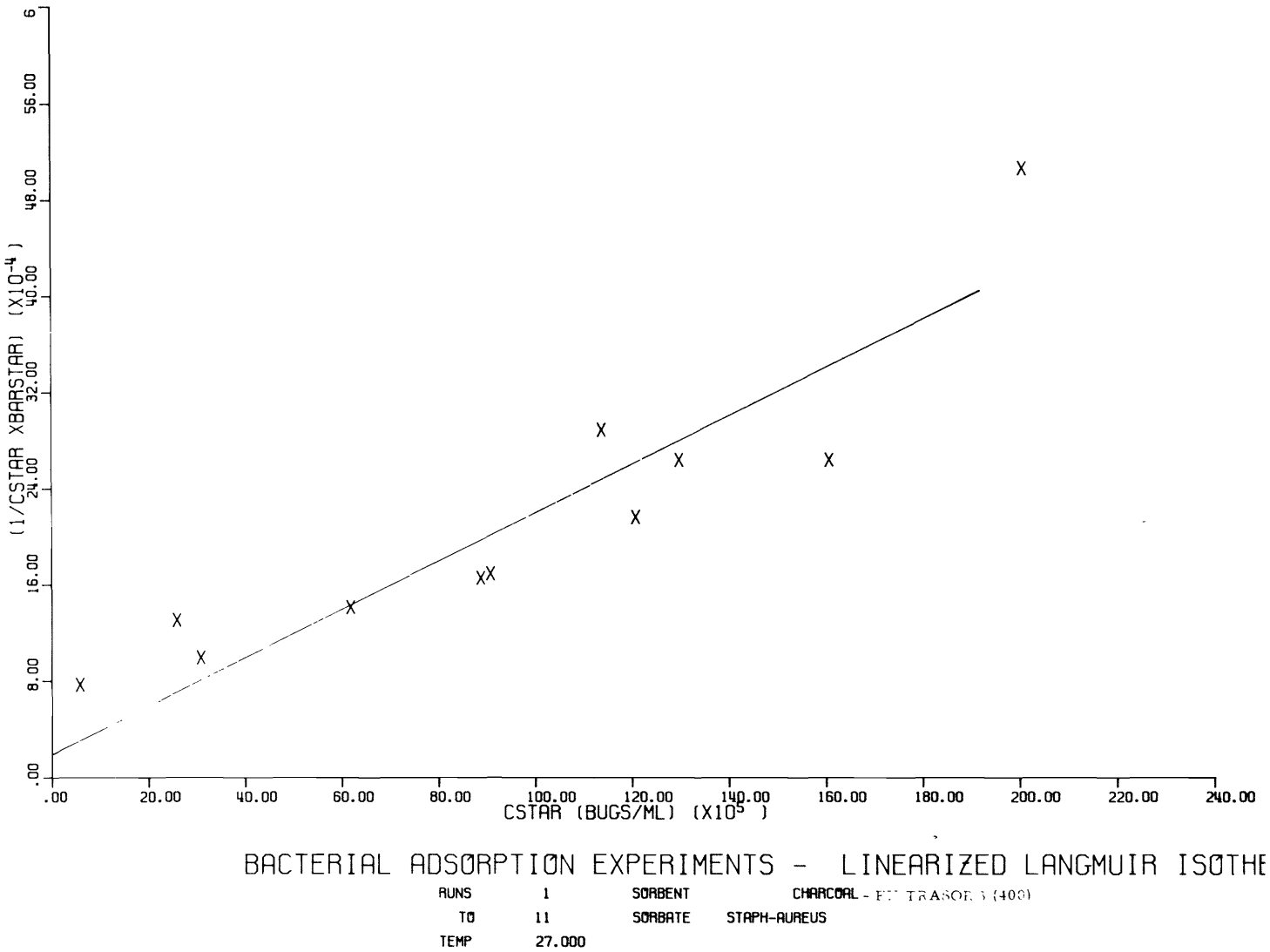


Figure D-9. Linearized Langmuir isotherm, runs 1-11—*S. aureus* and activated charcoal, 27C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 11/15/69
RUNS 1 TO 11

SORBATE STAPH-AUREUS FDA-209
SORBENT CHARCOAL FILTRASORB-400
TEMP 37.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .980
RSQ = .960
YINTERCEPT = 1/(ALPHA*XMAX) = .203272-03
SLOPE OF BEST FIT = .117907-09
ALPHA = .580048-06
XMAX = .848124+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
1	11/15/69	.18500+08	.90000+10	.20556-02
2	11/15/69	.13500+08	.75000+10	.18000-02
3	11/18/69	.26000+07	.45000+10	.57778-03
4	11/18/69	.56000+07	.65000+10	.10154-02
5	11/25/69	.10000+08	.80000+10	.12500-02
6	11/25/69	.24000+08	.72000+10	.33333-02
7	11/26/69	.15000+08	.75000+10	.20000-02
8	11/26/69	.37000+07	.50000+10	.74000-03
9	11/27/69	.10000+07	.25000+10	.40000-03
10	11/27/69	.14000+08	.85000+10	.16471-02
11	11/28/69	.11300+08	.79000+10	.14714-02

Figure D-10. Analysis of equilibrium data, runs 1-11—*S. aureus* and activated charcoal, 37C.

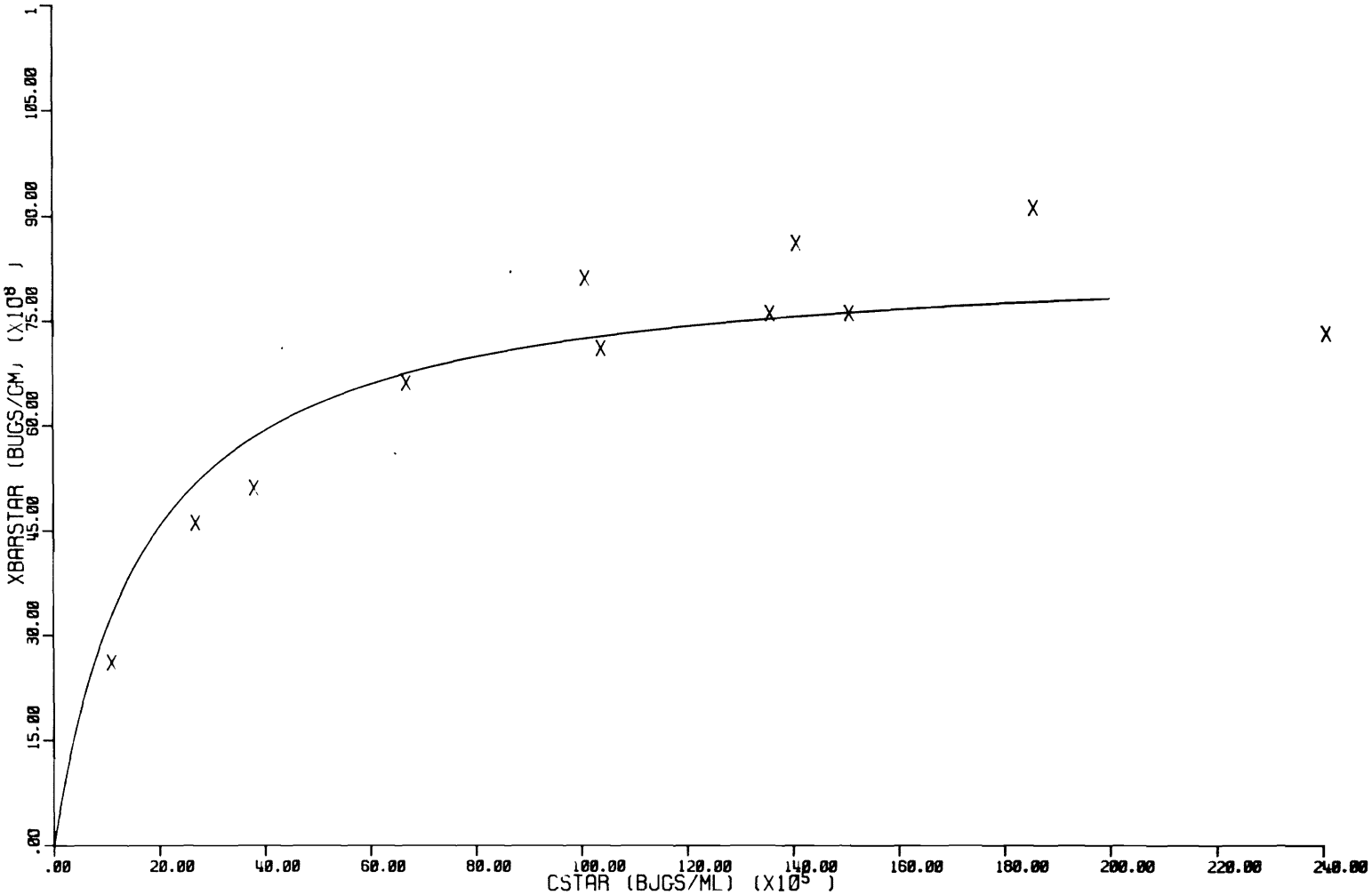


Figure D-11. Langmuir isotherm, runs 1-11—*S. aureus* and activated charcoal, 37C.

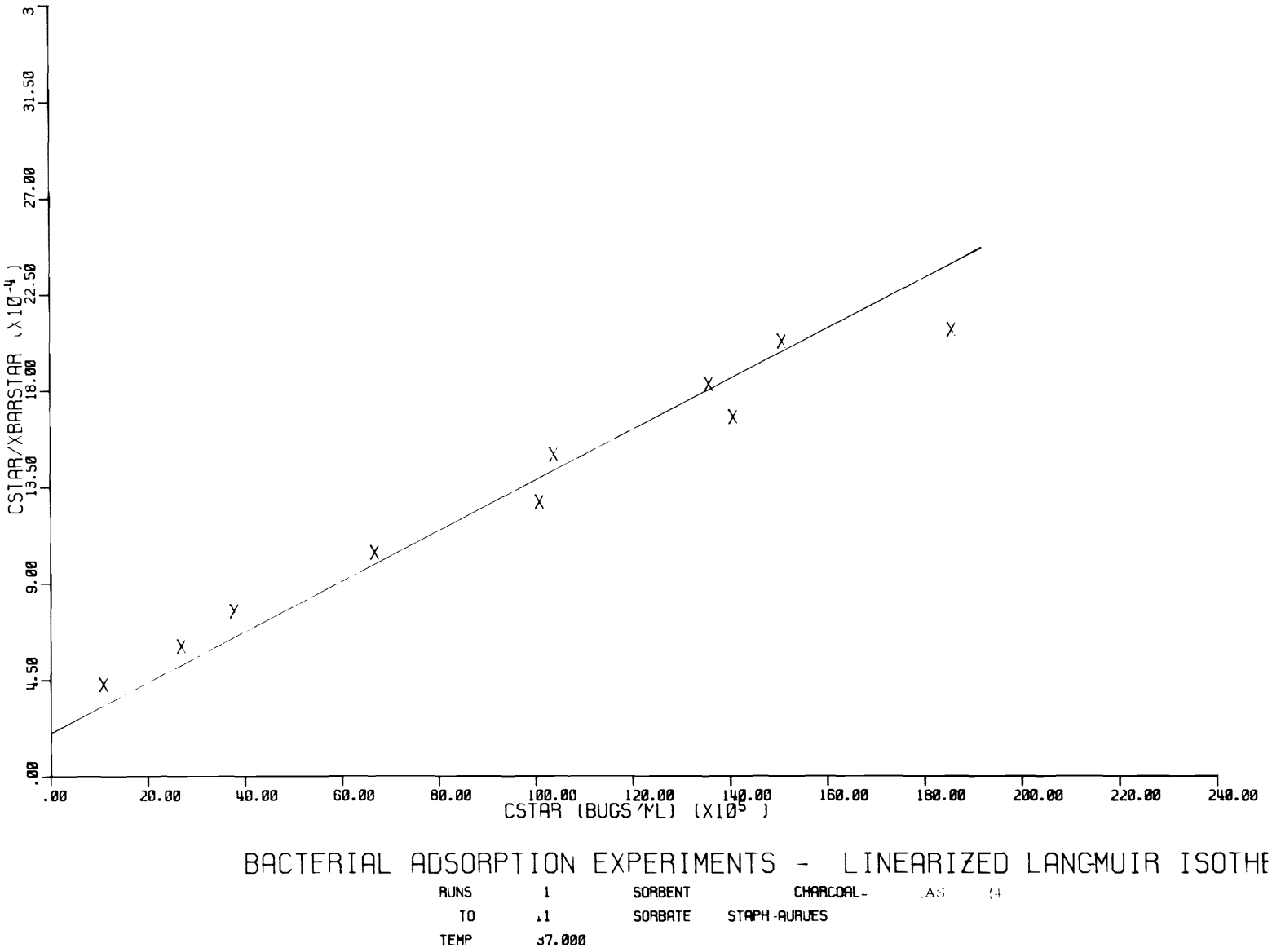


Figure D-12. Linearized Langmuir isotherm, runs 1-11—*S. aureus* and activated charcoal, 37C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 07/16/69
RUNS 1 TO 17

SORBATE STAHP-AUREUS FDA-209
SORBENT CLAY KAOLINITE
TEMP 10 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .548
RSQ = .300
YINTERCEPT = 1/(ALPHA*XMAX) = .138578-03
SLOPE OF BEST FIT = .240980-11
ALPHA = .173895-07
XMAX = .414972+12

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	(1/C**XBAR*)
1	07/16/69	.80000+08	.26000+12	.30769-03
2	07/16/69	.18000+09	.34000+12	.52941-03
3	07/17/69	.21000+08	.22000+12	.95455-04
4	07/17/69	.17000+09	.28000+12	.60714-03
5	07/18/69	.38000+08	.24500+12	.15510-03
6	07/18/69	.72000+08	.36200+12	.19890-03
7	07/18/69	.50000+08	.42000+12	.11905-03
8	07/19/69	.26000+08	.10000+12	.26000-03
9	07/19/69	.10000+09	.26000+12	.38462-03
10	07/18/69	.14500+08	.46000+11	.31522-03
11	07/18/69	.45000+08	.90000+11	.50000-03
12	07/18/69	.50000+08	.10000+12	.50000-03
13	07/19/69	.10000+09	.25000+12	.40000-03
14	07/19/69	.30000+08	.10000+12	.30000-03
15	07/16/69	.21000+09	.53000+12	.39623-03
16	07/16/69	.12400+09	.22000+12	.56364-03
17	07/16/69	.19000+09	.56000+12	.33929-03

Figure D-13. Analysis of equilibrium data, runs 1-17, *S. aureus* and kaolinite, 10C.

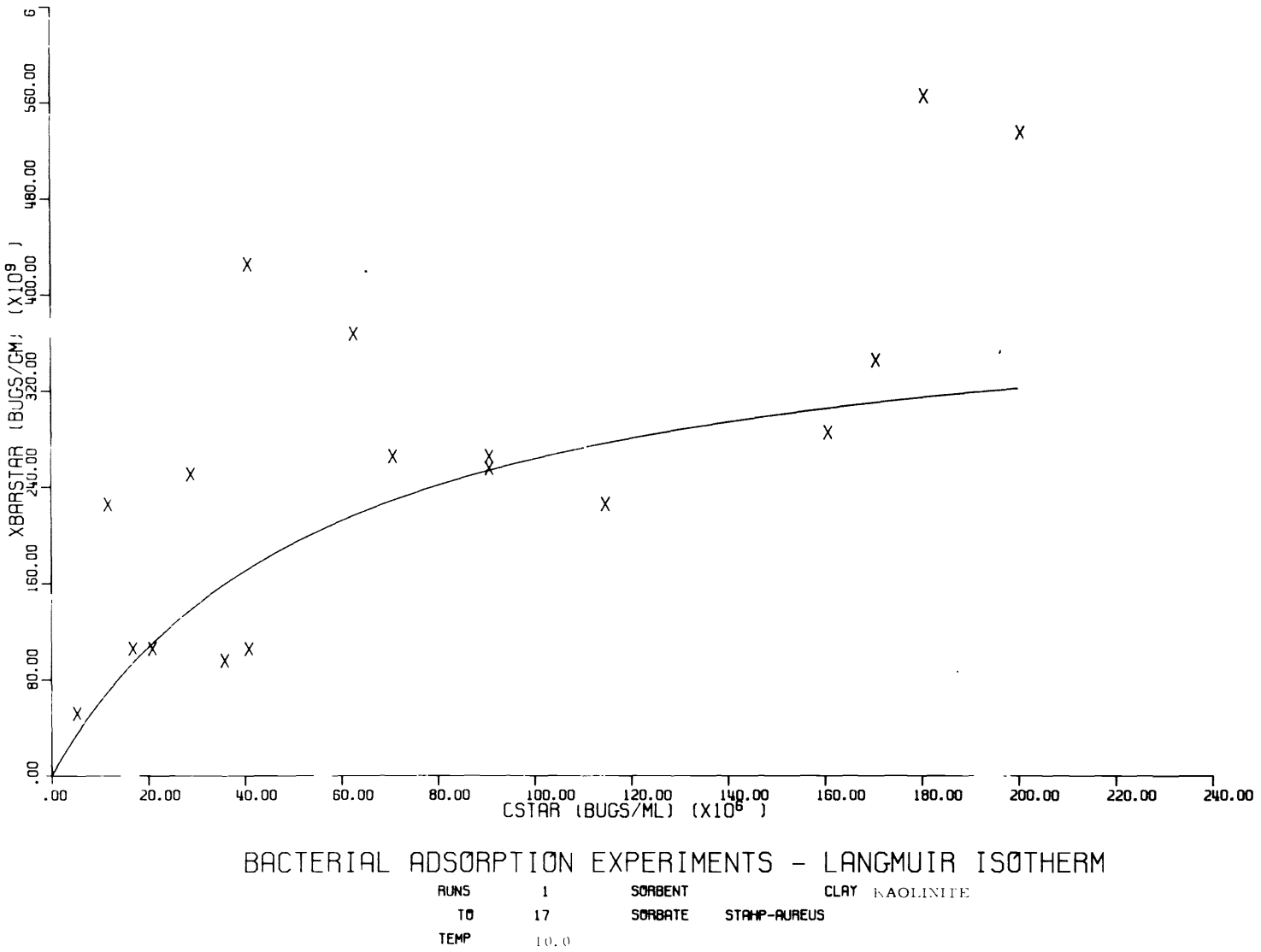


Figure D-14. Langmuir isotherm, runs 1-17, *S. aureus* and kaolinite, 10C.

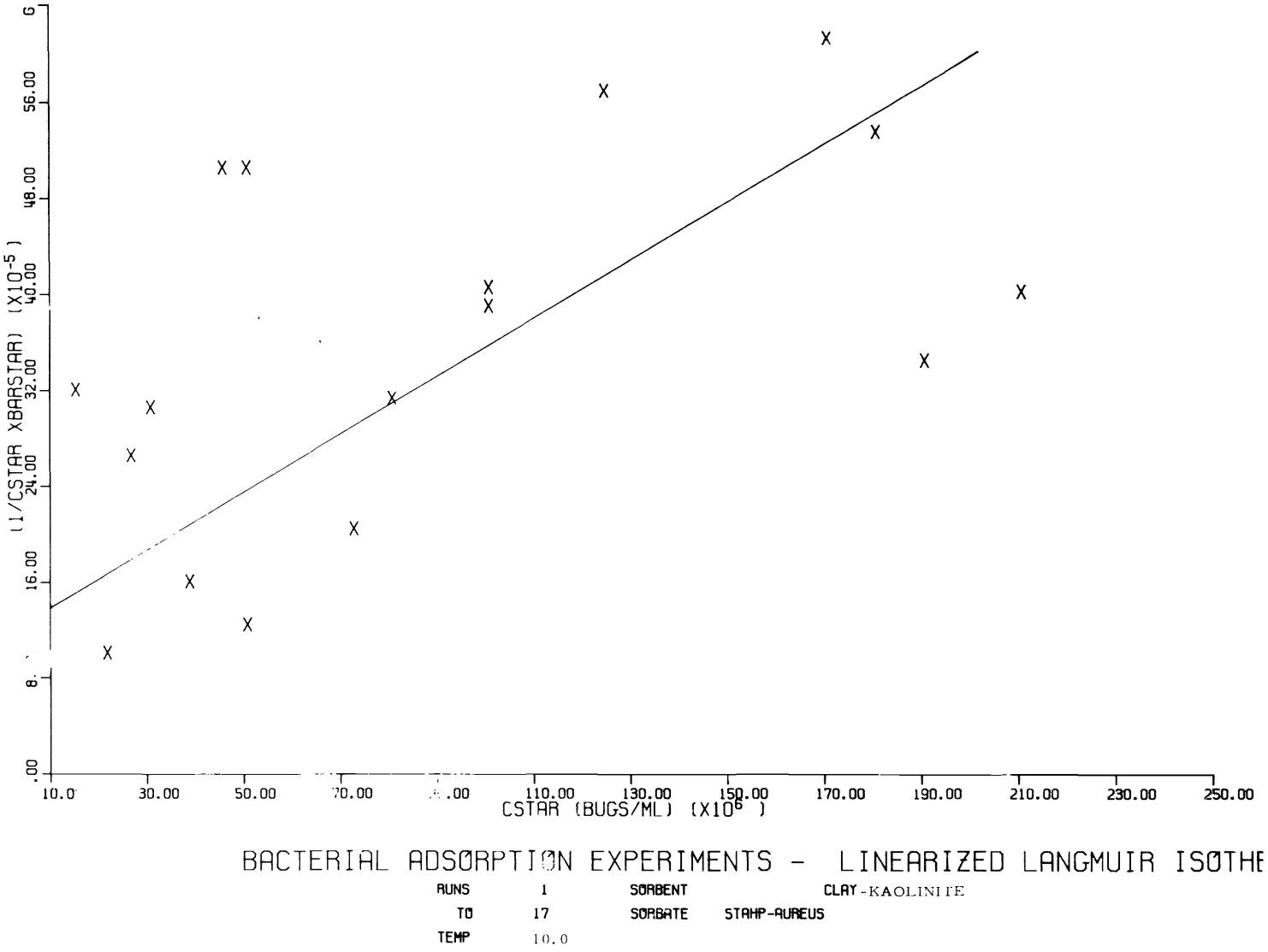


Figure D-15. Linearized Langmuir isotherm, runs 1-17, *S. aureus* and kaolinite, 10C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 07/23/69
RUNS 1 TO 11

SORBATE STAOH-AUREUS FDA-209
SORBENT CLAY KAOLINITE
TEMP 20 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R =	.844
RSQ =	.712
YINTERCEPT = 1/(ALPHA*XMAX) =	.11743E-03
SLOPE OF BEST FIT =	.23668E-11
ALPHA =	.20154E-07
XMAX =	.42250E+12

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	(1/C**XBAR*)
1	07/23/69	.32000E+08	.13000E+12	.24615E-03
2	07/23/69	.40000E+08	.40000E+12	.10000E-03
3	07/23/69	.12600E+09	.22000E+12	.57273E-03
4	07/23/69	.19000E+09	.32000E+12	.59375E-03
5	07/24/69	.18000E+08	.10000E+12	.18000E-03
6	07/24/69	.24000E+08	.18000E+12	.13333E-03
7	07/24/69	.67000E+08	.15000E+12	.44667E-03
8	07/24/69	.13500E+09	.35000E+12	.38571E-03
9	08/15/69	.21500E+09	.30000E+12	.71667E-03
10	08/15/69	.24500E+09	.48000E+12	.51042E-03
11	08/15/69	.22000E+09	.43000E+12	.51163E-03

Figure D-16. Analysis of equilibrium data, runs 1-11, *S. aureus* and kaolinite, 20C.

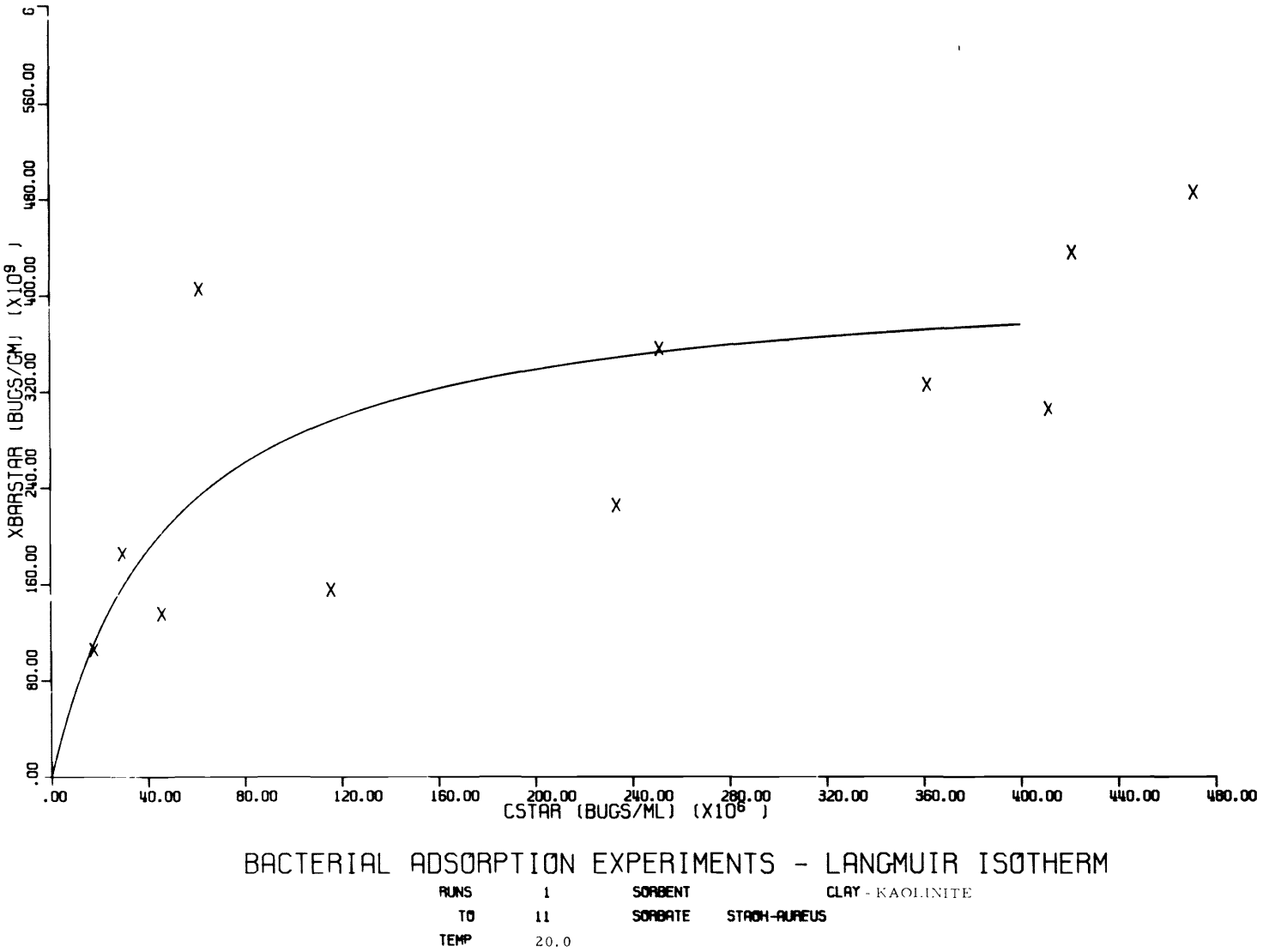


Figure D-17. Langmuir isotherm, runs 1-11, *S. aureus* and kaolinite, 20C

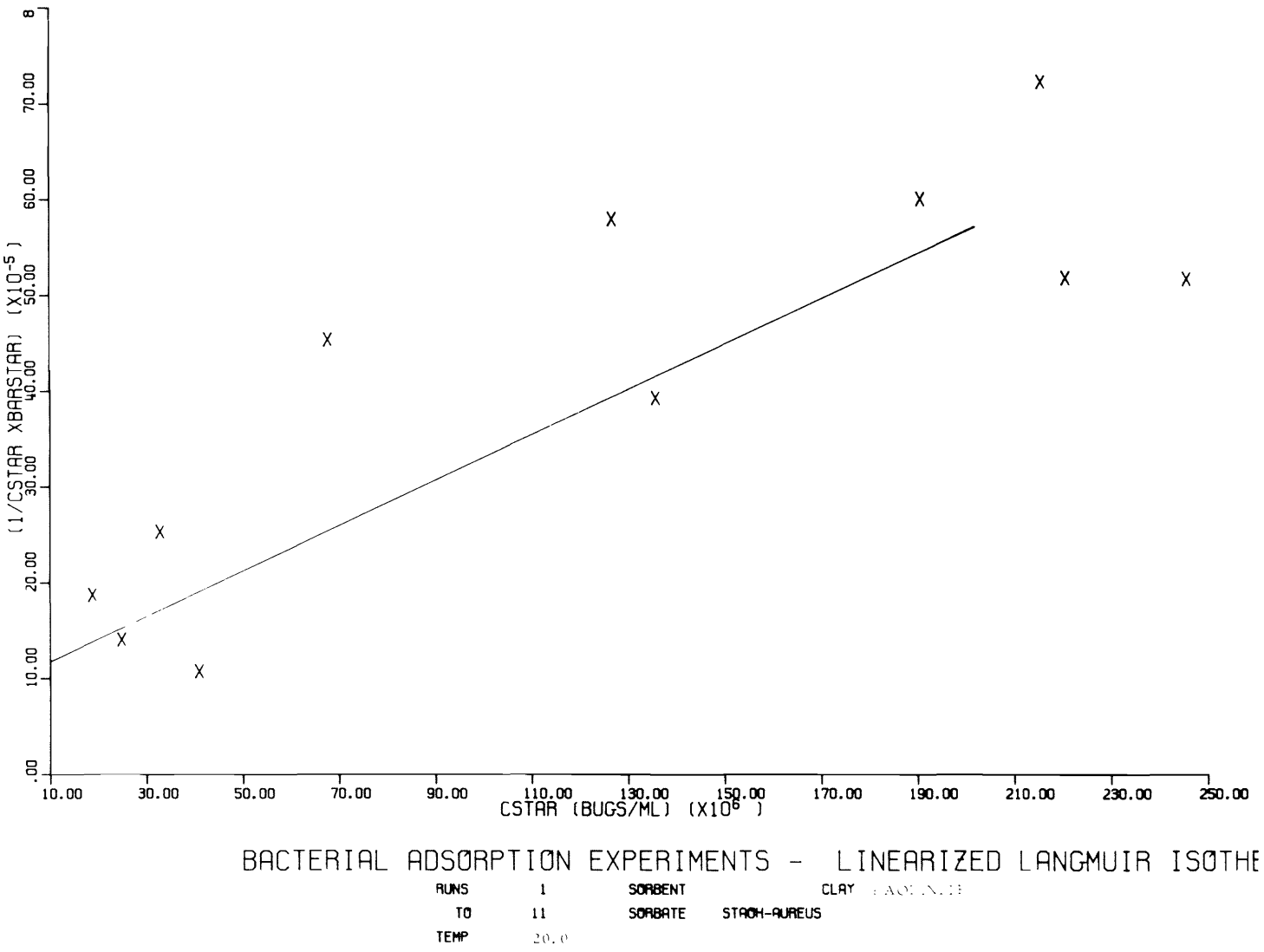


Figure D-18. Linearized Langmuir isotherm, runs 1-11, *S. aureus* and kaolinite, 20C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 07/31/69
RUNS 1 TO 16

SORBATE STAPH-AUREUS FDA-209
SORBENT CLAY KAOLINITE
TEMP 27 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .785
RSQ = .616
YINTEPCEPT = 1/(ALPHA*XMAX) = .105152-03
SLOPE OF BEST FIT = .210444-11
ALPHA = .200133-07
XMAX = .475186+12

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	(1/C**XBAR*)
1	07/31/69	.14000+08	.90000+11	.15556-03
1	07/31/69	.90000+08	.24000+12	.37500-03
3	07/31/69	.95000+08	.44000+12	.21591-03
4	07/31/69	.85000+08	.40000+12	.21250-03
5	08/01/69	.16000+08	.80000+11	.20000-03
6	08/01/69	.12000+09	.32500+12	.36923-03
7	08/01/69	.80000+08	.36000+12	.22222-03
8	08/01/69	.14000+09	.42000+12	.33333-03
9	08/02/69	.13000+08	.56000+11	.23214-03
10	08/02/69	.15000+08	.17000+12	.88235-04
11	08/02/69	.12000+09	.30000+12	.40000-03
12	08/02/69	.12000+09	.30000+12	.40000-03
13	08/13/69	.13000+09	.43000+12	.30233-03
14	08/13/69	.93000+08	.28000+12	.33214-03
15	08/13/69	.93000+08	.28000+12	.33214-03
16	08/13/69	.90000+08	.32500+12	.27692-03

Figure D-19. Analysis of equilibrium data, runs 1-16, *S. aureus* and kaolinite, 27C.

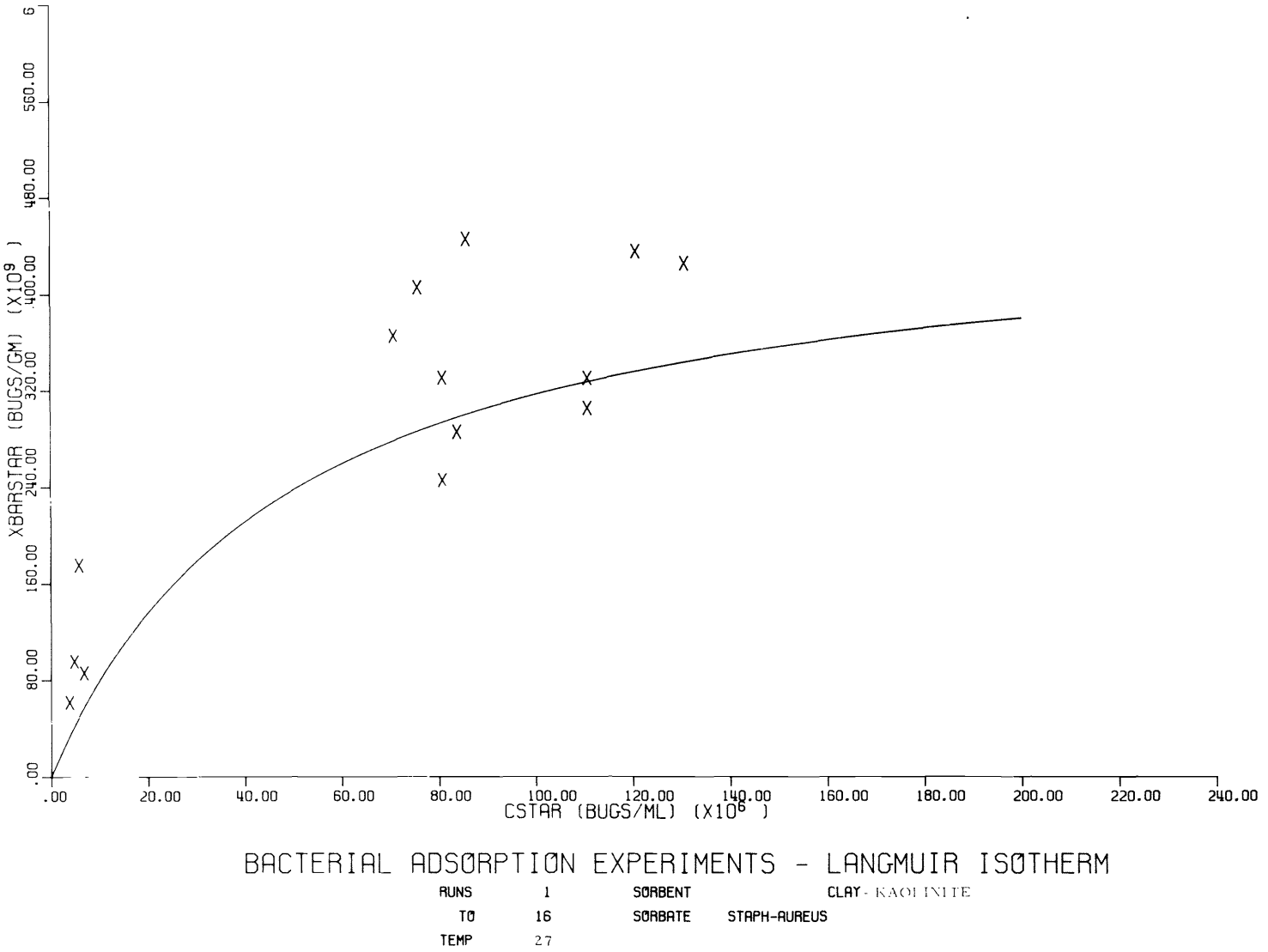


Figure D-20. Langmuir isotherm, runs 1-16, *S. aureus* and kaolinite, 27C.

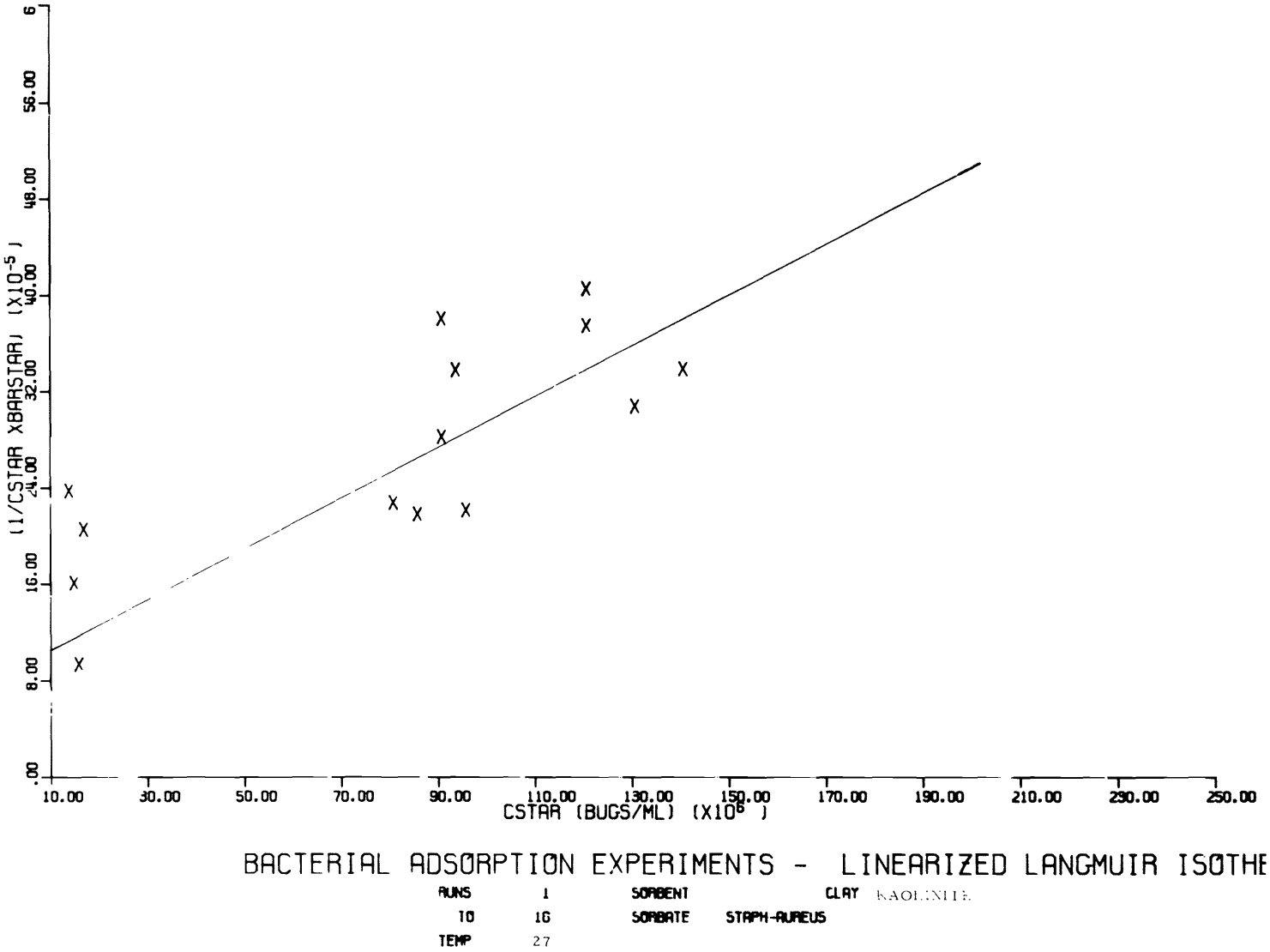


Figure D-21. Linearized Langmuir isotherm, runs 1-16, *S. aureus* and kaolinite, 27C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 06/19/69
RUNS 1 TO 19

SORBATE STAPH-AUREUS FDA-209
SORBENT CLAY KAOLINITE
TEMP 37 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .797
RSQ = .636
YINTERCEPT = 1/(ALPHA*XMAX) = .349684-04
SLOPE OF BEST FIT = .372185-11
ALPHA = .355544-07
XMAX = .330923+12

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	(1/C**XBAR*)
1	06/19/69	.15000+08	.70000+11	.21429-03
2	06/20/69	.30000+07	.80000+10	.37500-03
3	06/20/69	.26000+07	.13000+11	.20000-03
4	06/20/69	.37500+07	.16000+11	.23437-03
5	06/21/69	.48000+08	.24500+12	.19592-03
6	06/24/69	.42000+08	.26500+12	.18113-03
7	06/25/69	.30000+08	.30000+12	.10000-03
8	06/26/69	.95000+08	.45000+12	.18889-03
9	06/26/69	.12500+09	.32000+12	.39062-03
10	06/27/69	.70000+08	.12000+12	.16667-03
11	06/27/69	.10000+09	.25000+12	.40000-03
12	06/27/69	.17500+09	.33000+12	.53030-03
13	06/28/69	.25000+08	.70000+12	.10000-03
14	06/28/69	.30000+08	.40000+12	.75000-04
15	06/28/69	.50000+08	.35000+12	.14286-03
16	08/07/69	.14000+09	.38000+12	.36842-03
17	08/07/69	.17500+09	.28000+12	.48214-03
18	08/07/69	.14500+09	.24000+12	.60417-03
19	08/07/69	.14200+09	.22000+12	.64545-03

Figure D-22. Analysis of equilibrium data, runs 1-19, *S. aureus* and kaolinite, 37C.

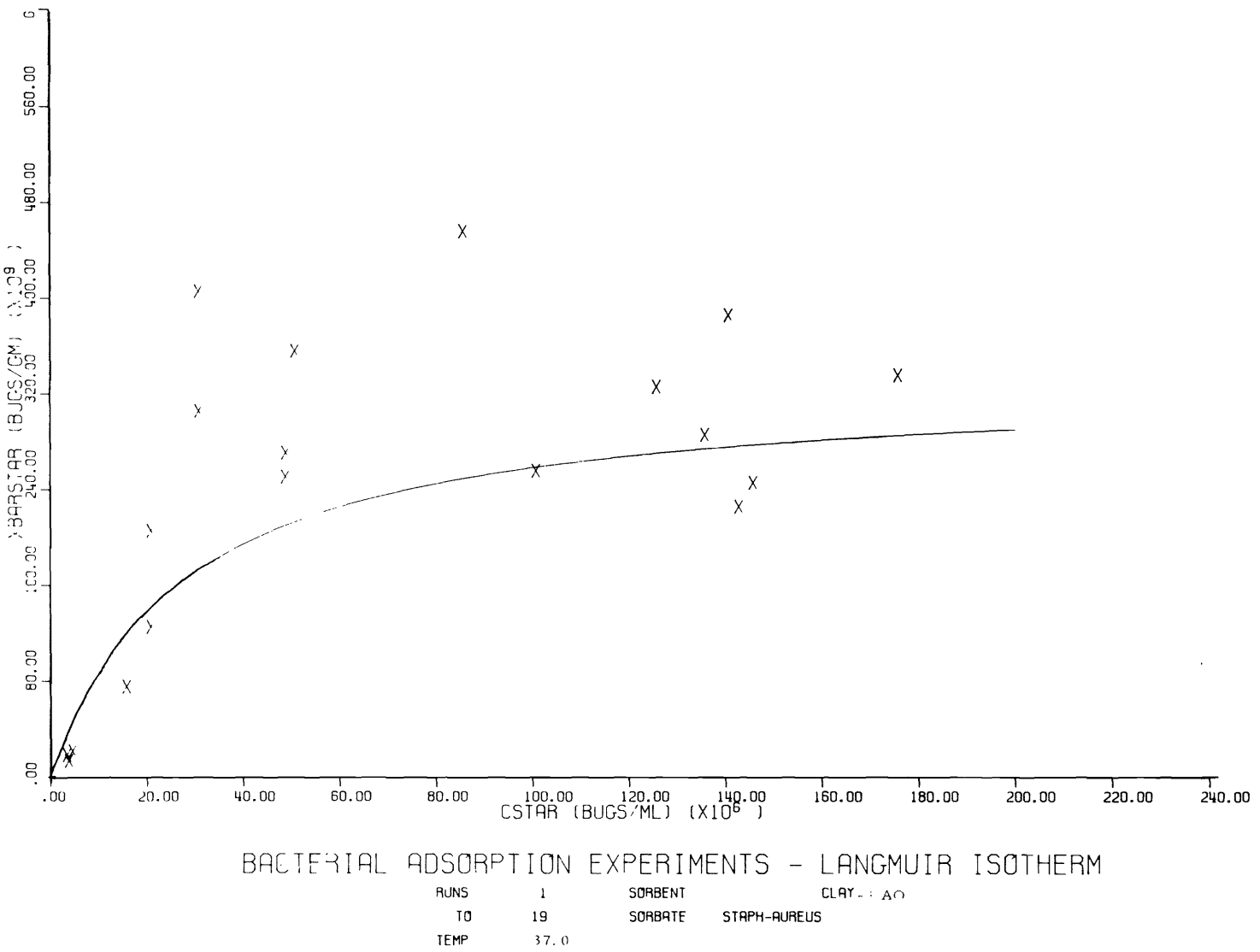


Figure D-23. Langmuir isotherm, runs 1-19, *S. aureus* and kaolinite, 37C.

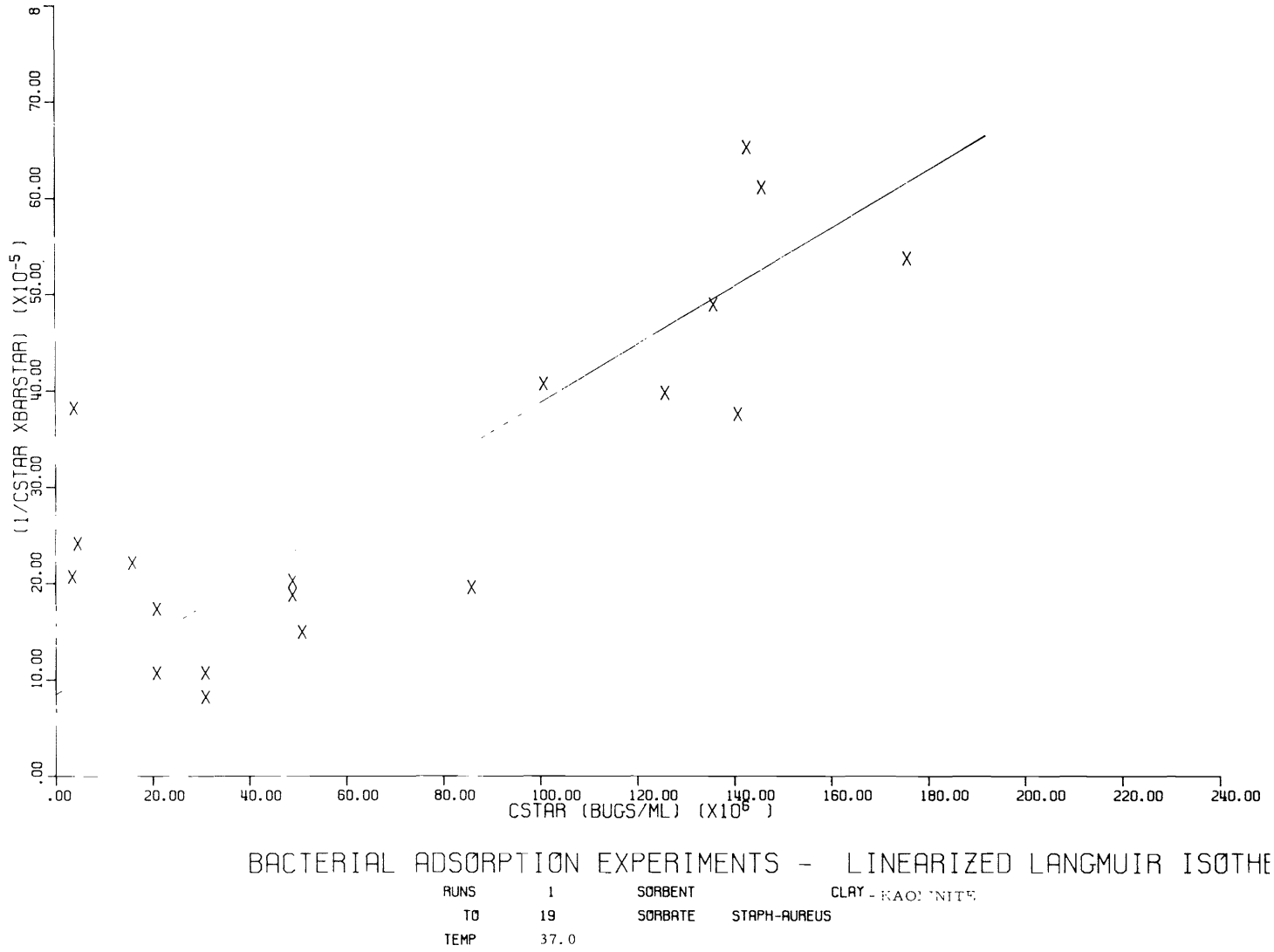


Figure D-24. Linearized Langmuir isotherm, runs 1-19, *S. aureus* and kaolinite, 37C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 10/15/69
RUNS 5 TO 18

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM MENDON
TEMP 10.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .835
RSQ = .701
YINTERCEPT = 1/(ALPHA*XMAX) = .175168-02
SLOPE OF BEST FIT = .907448-10
ALPHA = .515761-07
XMAX = .110587+11

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

	RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
	5	10/15/69	.47000+08	.11000+11	.42727-02
	6	10/15/69	.33000+08	.10000+11	.33000-02
	8	10/17/69	.75000+08	.12000+11	.62500-02
	9	10/17/69	.33000+08	.45000+10	.73333-02
	10	10/17/69	.40000+08	.87000+10	.45977-02
	11	10/17/69	.30000+08	.70000+10	.42857-02
	12	10/17/69	.18500+08	.24000+10	.77083-02
	18	10/23/69	.60000+08	.90000+10	.66667-02
⊗	16	10/23/69	.73000+08	.40000+10	.18250-01
⊗	17	10/23/69	.70000+08	.45000+10	.15556-01
Δ	2	10/15/69	.70000+08	.23000+11	.30435-02
Δ	3	10/15/69	.66000+08	.17000+11	.38824-02
Δ	4	10/15/69	.55000+08	.15800+11	.34810-02
Δ	14	10/23/69	.13300+09	.45000+10	.29556-01
Δ	15	10/23/69	.12000+09	.65000+10	.18462-01

⊗ Deleted from regression analysis but plotted on Figures

Δ Off the scale, therefore not shown in Figures

Figure D-25. Analysis of equilibrium data, runs 5-18, *S. aureus* and Mendon silt loam, 10C.

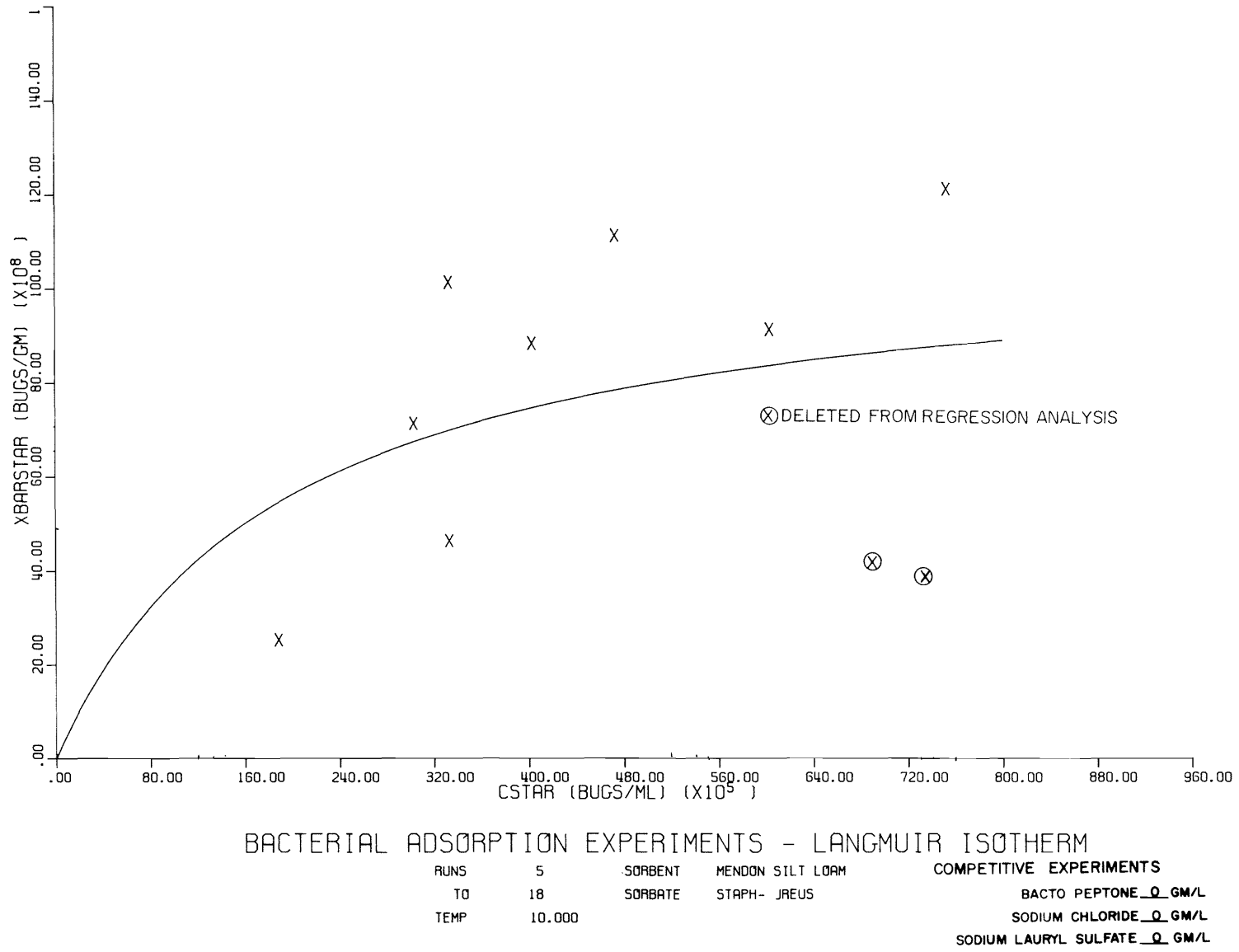


Figure D-26. Langmuir isotherm, runs 5-18, *S. aureus* and Mendon silt loam, 10C.

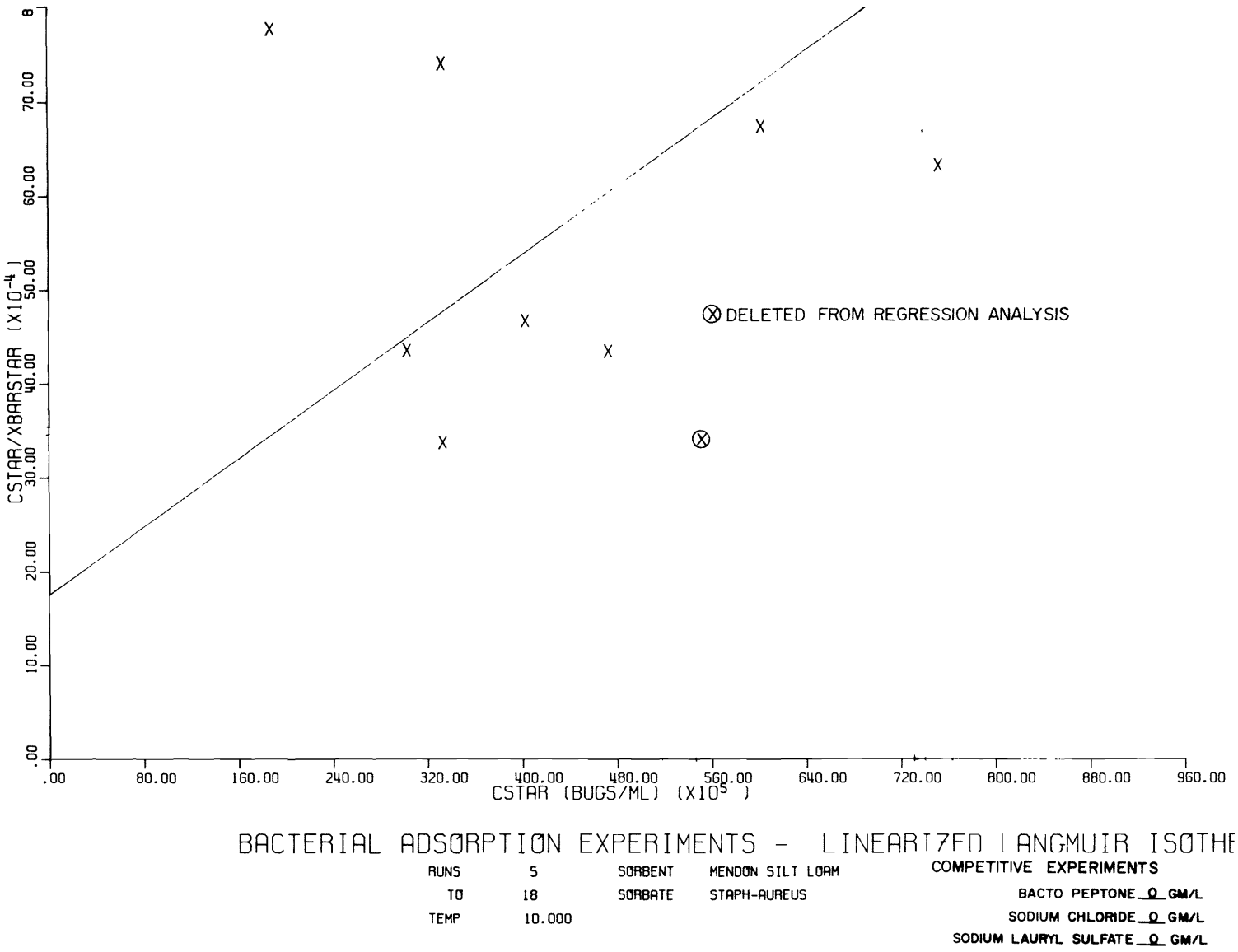


Figure D-27. Linearized Langmuir isotherm, runs 5-18, *S. aureus* and Mendon silt loam, 10C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 01022070
RUNS 3 TO 15

SORBATE STAPH-AUREUS
FDA-209
SORBENT SOIL
MENDON SILT LOAM
TEMP 20.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .980
RSQ = .961
YINTERCEPT = 1/(ALPHA*XMAX) = .788731-03
SLOPE OF BEST FIT = .666689-10
ALPHA = .845268-07
XMAX = .149995+11

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

	RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
	3	01022070	.50000+08	.16000+11	.31250-02
	4	01022070	.35000+08	.90000+10	.38889-02
	5	01022070	.20000+08	.80000+10	.25000-02
	7	01025070	.11000+09	.14000+11	.78571-02
	9	01025070	.50000+08	.14000+11	.35714-02
	11	01028070	.15500+09	.14000+11	.11071-01
	13	01028070	.11000+09	.14000+11	.78571-02
	14	01028070	.10000+09	.12800+11	.78125-02
	15	01028070	.85000+08	.12000+11	.70833-02
⊗	12	01002070	.14500+09	.11000+11	.13182-01
Δ	1	01002070	.70000+08	.20000+11	.35000-02
Δ	2	01002070	.58000+08	.17000+11	.34118-02
Δ	8	01002070	.78000+08	.16000+11	.48750-02

⊗ Deleted from regression analysis but plotted on Figures

Δ Off the scale, therefore not shown in Figures

Figure D-28. Analysis of equilibrium data, runs 3-15, *S. aureus* and Mendon silt loam, 20C.

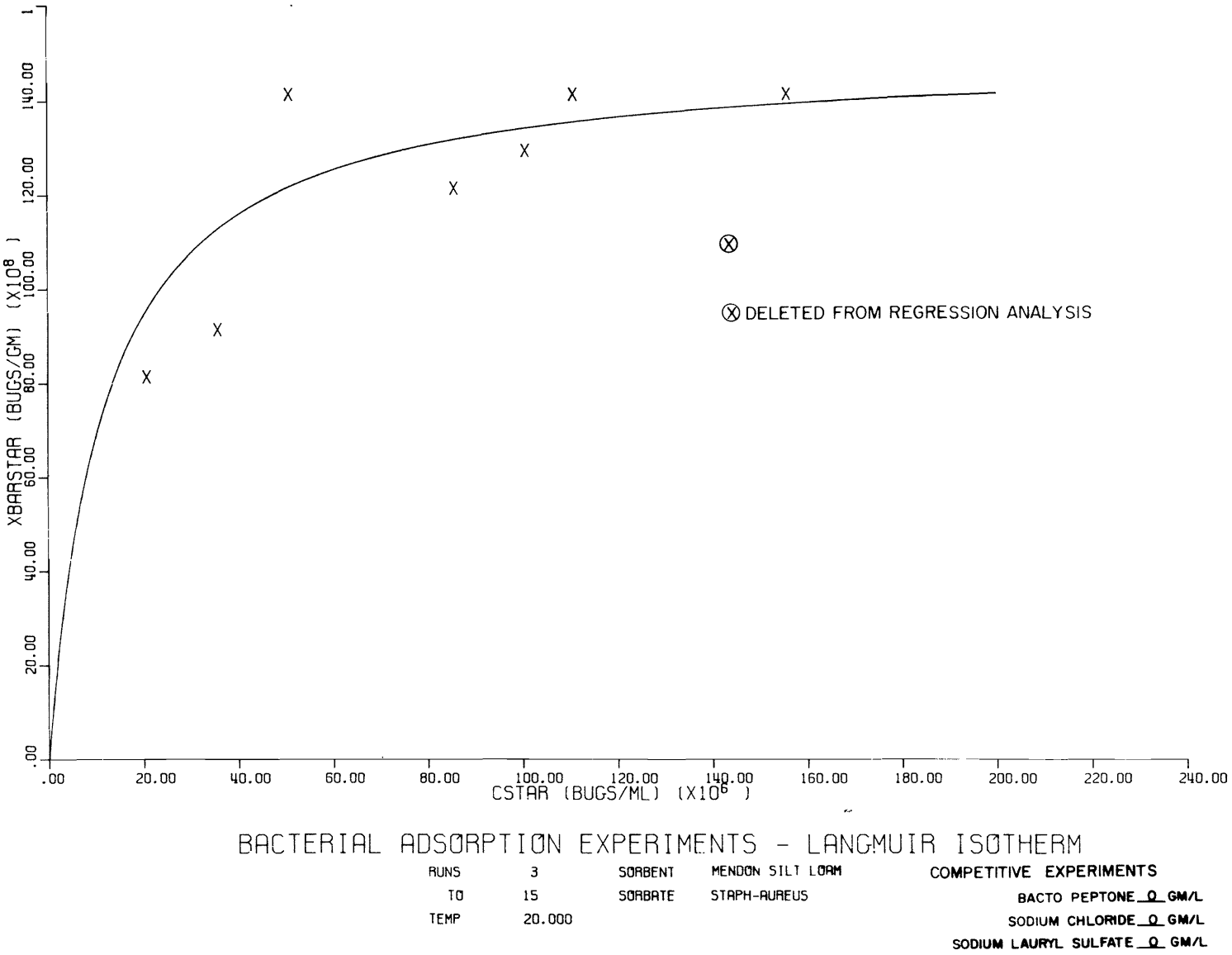


Figure D-29. Langmuir isotherm, runs 3-15, *S. aureus* and Mendon silt loam, 20C.

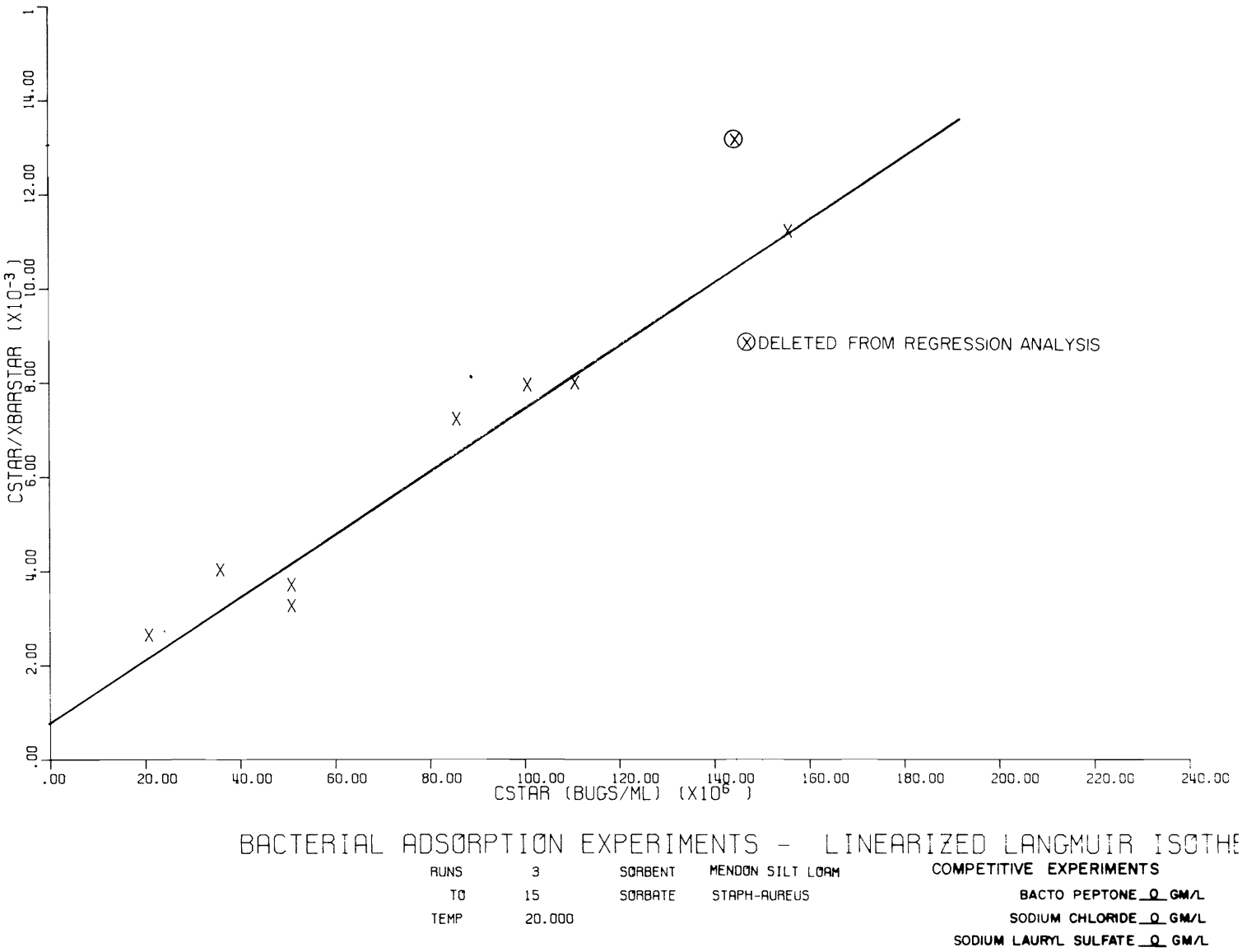


Figure D-30. Linearized Langmuir isotherm, runs 3-15, *S. aureus* and Mendon silt loam, 20C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 10/01/69
RUNS 2 TO 18

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL MENDON SILT LOAM
TEMP 27.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .766
RSQ = .587
YINTERCEPT = 1/(ALPHA*XMAX) = .37363-03
SLOPE OF REST FIT = .49971D-10
ALPHA = .133754-06
XMAX = .200116+11

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	(1/C**XBAR*)
2	10/01/69	.14300+09	.75000+10	.19067-01
3	10/01/69	.24000+09	.33000+11	.72727-02
4	10/01/69	.28000+09	.28000+11	.10000-01
5	10/03/69	.38000+07	.14000+10	.27143-02
6	10/03/69	.60000+07	.34000+10	.17647-02
7	10/03/69	.13500+08	.50000+10	.27000-02
8	10/03/69	.10000+09	.23000+11	.43478-02
10	10/07/69	.32000+09	.20000+11	.16000-01
11	10/07/69	.21000+09	.20000+11	.10500-01
12	10/07/69	.22000+09	.27000+11	.81481-02
13	10/07/69	.12000+09	.36000+11	.33333-02
15	10/09/69	.20000+07	.40000+10	.50000-03
16	10/09/69	.65000+07	.63000+10	.10317-02
17	10/09/69	.18000+08	.15000+11	.12000-02
18	10/09/69	.52000+08	.14000+11	.37143-02

Figure D-31. Analysis of equilibrium data, runs 2-18, *S. aureus* and Mendon silt loam, 27C.

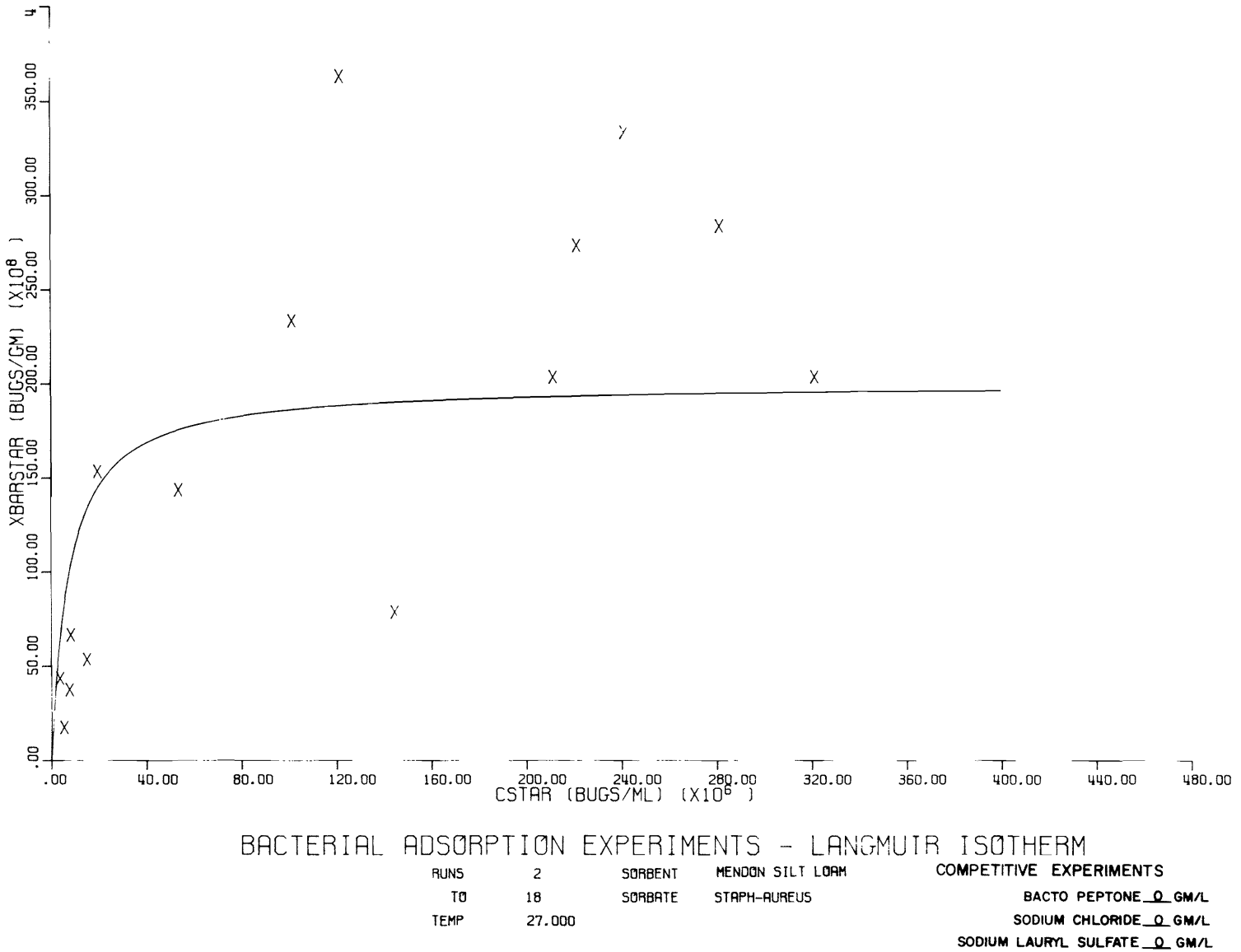


Figure D-32. Langmuir isotherm, runs 2-18, *S. aureus* and Mendon silt loam, 27C.

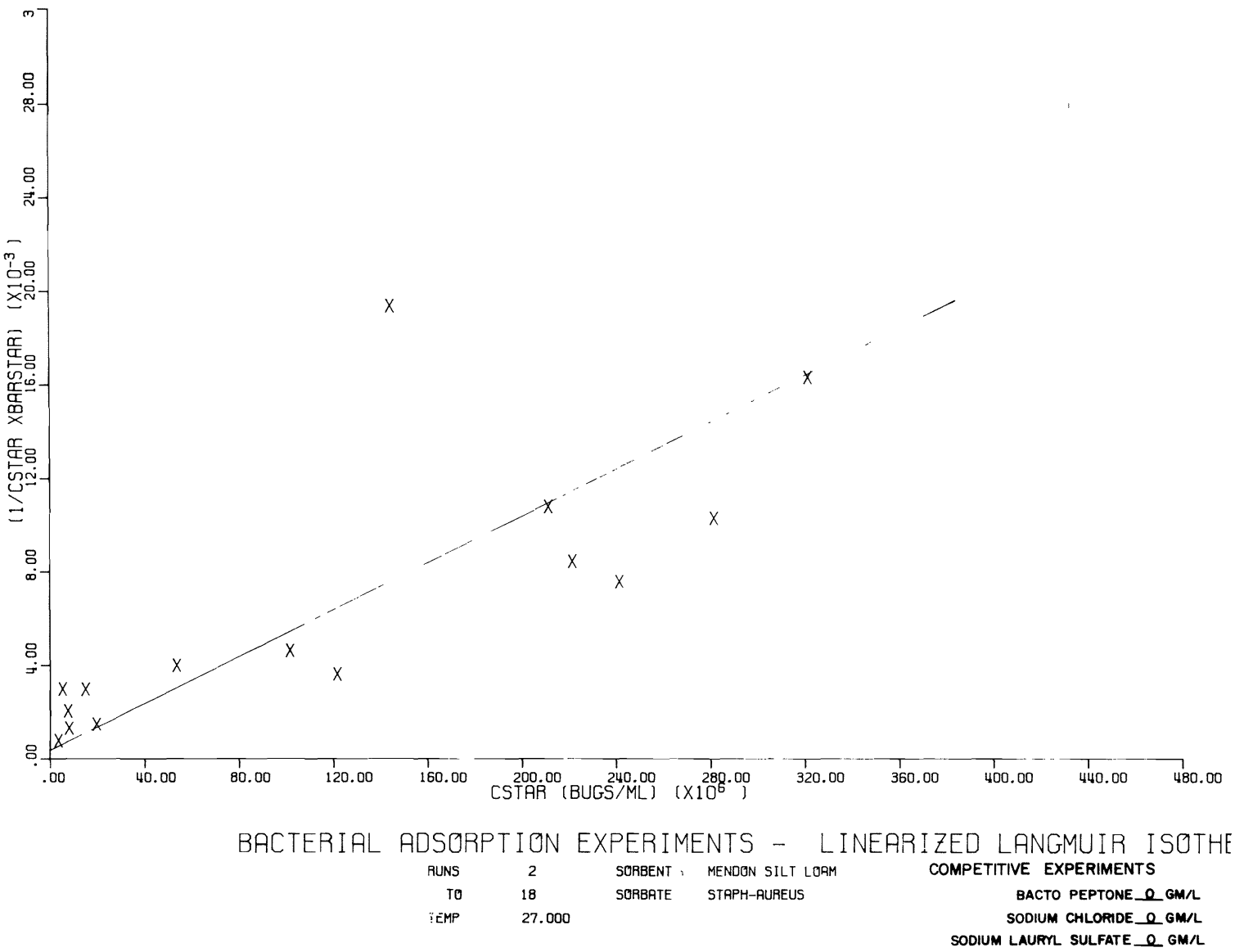


Figure D-33. Linearized Langmuir isotherm, runs 2-18, *S. aureus* and Mendon silt loam, 27C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 01/16/70
RUNS 1 TO 9

SORBATE STAPH-AUREUS FDA-209
SORBENT SOIL MENDON SILT LOAM
TEMP 37.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R =	.996
RSQ =	.992
Y INTERCEPT = 1/(ALPHA*XMAX) =	.214552-03
SLOPE OF BEST FIT =	.356697-10
ALPHA =	.166251-06
XMAX =	.280353+11

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

	RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
	1	01/16/70	.80000+08	.25000+11	.32000-02
	2	01/16/70	.55000+08	.25000+11	.22000-02
	3	01/16/70	.33000+08	.25000+11	.13200-02
	4	01/16/70	.20000+08	.24000+11	.83333-03
	8	01/20/70	.15000+09	.28000+11	.53571-02
	9	01/20/70	.10000+09	.25000+11	.40000-02
Δ	6	01/20/70	.24000+09	.24000+11	.10000-01
Δ	7	01/20/70	.20000+09	.23000+11	.86957-01
Δ	10	01/20/70	.28000+08	.32000+11	.87500-03

Δ Off the scale, therefore not shown in Figures

Figure D-34. Analysis of equilibrium data, runs 1-9, *S. aureus* and Mendon silt loam, 37C.

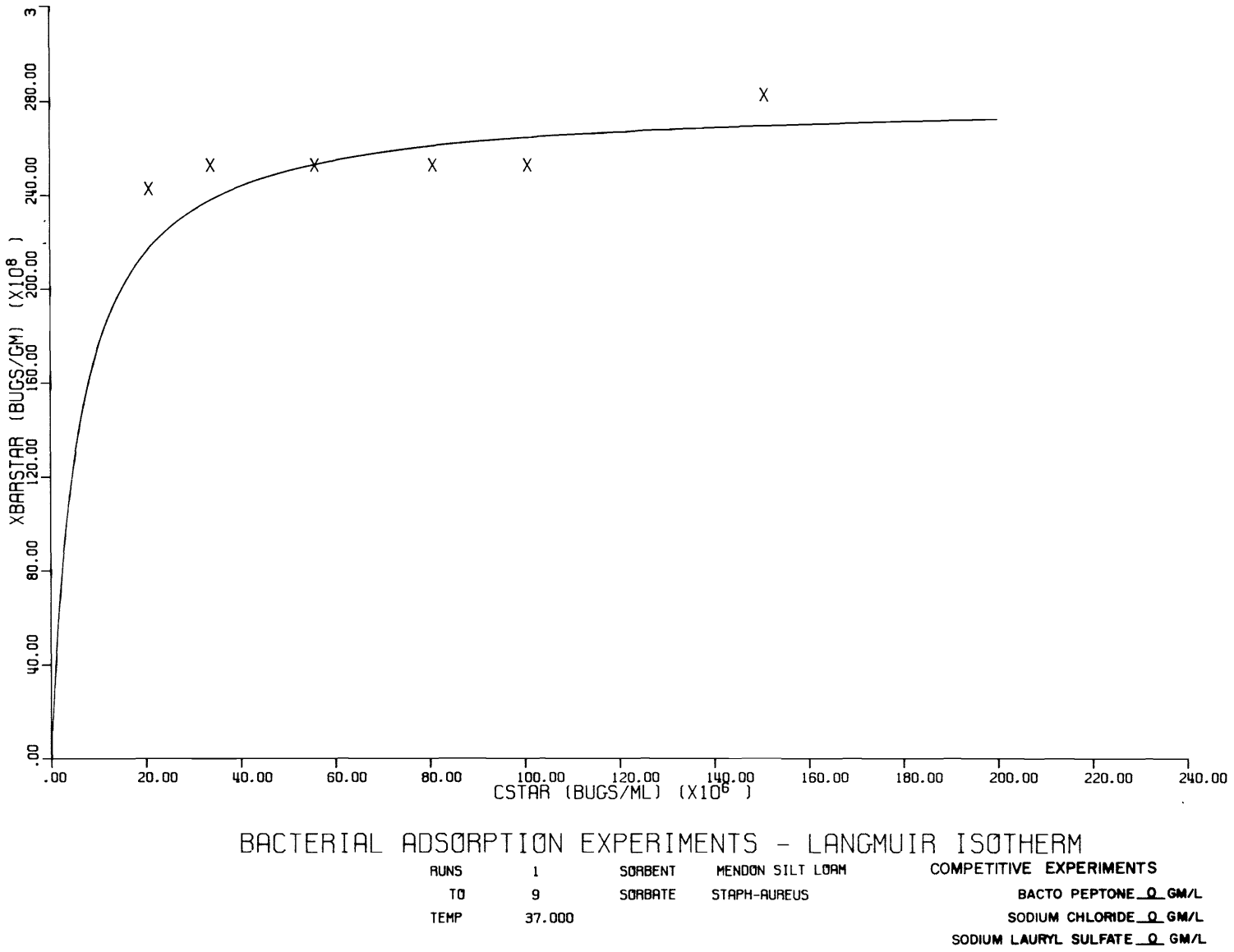


Figure D-35. Langmuir isotherm, runs 1-9, *S. aureus* and Mendon silt loam, 37C.

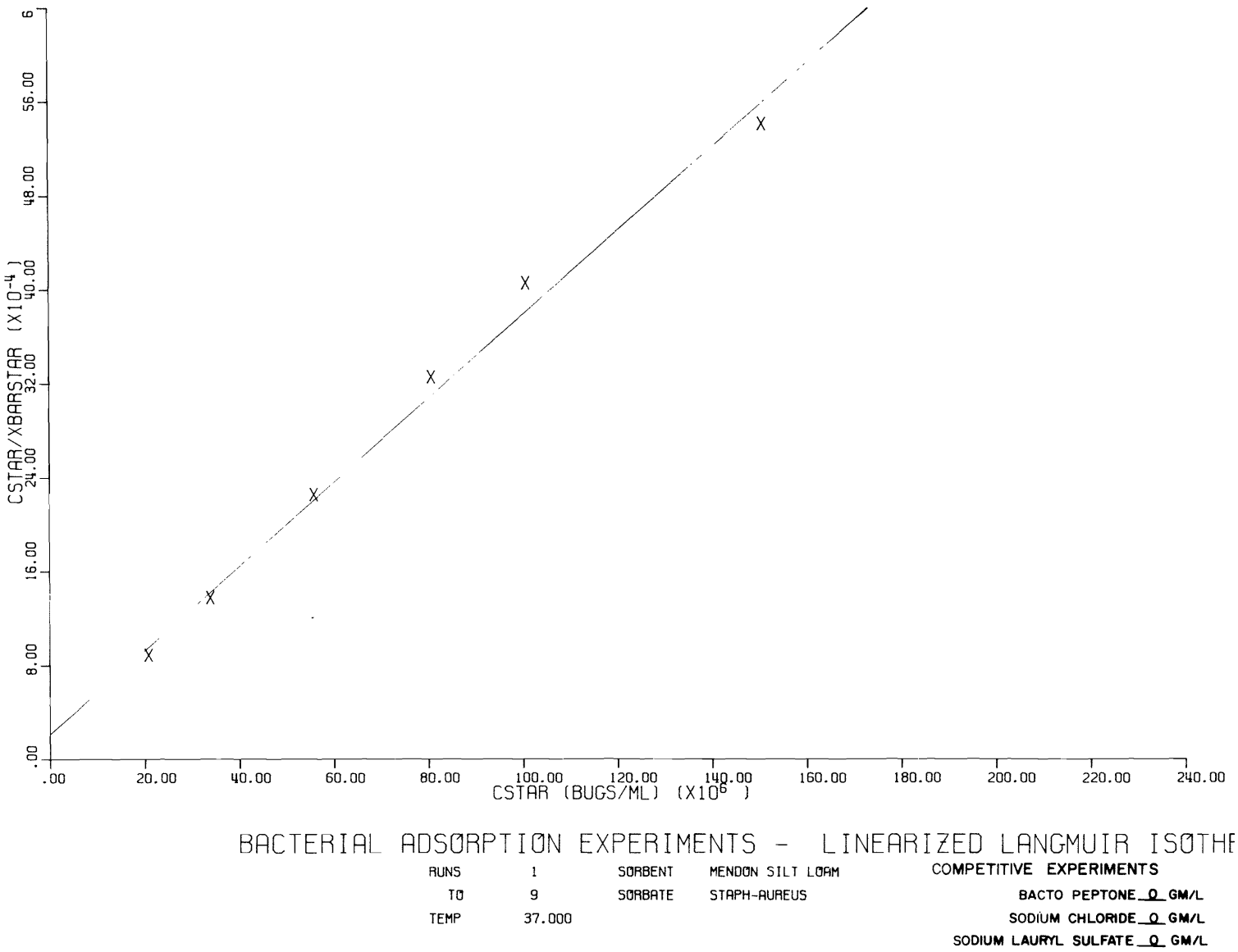


Figure D-36. Linearized Langmuir isotherm, runs 1-9, *S. aureus* and Mendon silt loam, 37C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 05/20/70
RUNS 2 TO 22

SORBATE STAPH-AUREUS
FDA-209
SORBENT SAND
SILICA
TEMP 10.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .999
RSQ = .998
Y INTERCEPT = 1/(ALPHA*XMAX) = .000007
SLOPE OF BEST FIT = .000001
ALPHA = .857143
XMAX = 166667

BASED UPON EQUILT RUN DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	05/20/70	.30000+07	.00000	.00000
3	05/20/70	.45000+07	.00000	.00000
4	05/20/70	.45000+07	.00000	.00000
5	05/20/70	.45000+07	.00000	.00000
7	05/22/70	.55000+07	.00000	.00000
8	05/22/70	.16500+08	.00000	.00000
9	05/22/70	.21000+08	.00001	.00000
10	05/22/70	.22500+08	.00000	.00000
11	05/22/70	.24000+08	.00000	.00000
12	05/27/70	.60000+07	.00000	.00000
13	05/27/70	.70000+07	.00000	.00000
14	05/27/70	.80000+07	.00000	.00000
15	05/27/70	.90000+07	.00000	.00000
17	05/30/70	.15500+08	.00000	.00000
18	05/30/70	.16500+08	.00000	.00000
19	05/30/70	.17000+08	.00000	.00000
20	05/30/70	.17500+08	.00000	.00000
21	05/30/70	.18000+08	.00000	.00000
22	05/30/70	.00000	.10000+04	.00000

Figure D-37. Analysis of equilibrium data, runs 2-22, *S. aureus* and silica sand, 37C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 04/21/70
RUNS 2 TO 16

SORBATE STAPH-AUREUS
FDA-209
SORBENT SAND
SILICA
TEMP 20.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .000
RSQ = .000
YINTERCEPT = 1/(ALPHA*XMAX) = .000000
SLOPE OF BEST FIT = .000000
ALPHA = .000000
XMAX = .000000

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	04/21/70	.29000+08	.00000	.00000
3	04/21/70	.34000+08	.00000	.00000
4	04/21/70	.41500+08	.00000	.00000
5	04/21/70	.48000+08	.00000	.00000
7	04/23/70	.49000+07	.00000	.00000
8	04/23/70	.59000+07	.00000	.00000
9	04/23/70	.85000+07	.00000	.00000
10	04/23/70	.90000+07	.00000	.00000
12	04/23/70	.35000+07	.00000	.00000
13	04/28/70	.50000+07	.00000	.00000
14	04/28/70	.65000+07	.00000	.00000
15	04/28/70	.90000+07	.00000	.00000
16	04/28/70	.00000	.10000+04	.00000

Figure D-38. Analysis of equilibrium data, runs 2-16, *S. aureus* and silica sand, 20C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 05/07/70
RUNS 2 TO 14

SORBATE STAPH-AUREUS
FDA-209
SORBENT SAND
SILICA
TEMP 37.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .000
RSQ = .000
Y INTERCEPT = 1/(ALPHA*XMAX) = .000000
SLOPE OF BEST FIT = .000000
ALPHA = .000000
XMAX = .000000

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	05/07/70	.95000+07	.00000	.00000
3	05/07/70	.10500+08	.00000	.00000
4	05/07/70	.10500+08	.00000	.00000
5	05/07/70	.14500+08	.00000	.00000
7	05/13/70	.10500+08	.00000	.00000
8	05/13/70	.14500+08	.00000	.00000
9	05/13/70	.17000+08	.00000	.00000
10	05/13/70	.18000+08	.00000	.00000
11	05/15/70	.20500+08	.00000	.00000
12	05/15/70	.25000+08	.00000	.00000
13	05/15/70	.26500+08	.00000	.00000
14	05/15/70	.00000	.10000+04	.00000

Figure D-39. Analysis of equilibrium data, runs 2-14, *S. aureus* and silica sand, 27C.

APPENDIX E

BACTERIAL ADSORPTION ISOTHERMS (WITH SLS COMPETITION)

Bacto-Peptone 0 gm/l
Sodium Chloride 0 gm/l
Sodium Lauryl Sulfate .05 gm/l

This appendix includes the bacterial adsorption isotherms obtained in the presence of sodium lauryl sulfate (SLS) (.05 gram per liter). These isotherms were obtained at 10C, 20C, 27C, and 37C. A summary of results of these isotherms is presented in Table 2.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 11/06/69
RUNS 1 TO 22

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAN .05LSG/L
TEMP 10.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .000
RSQ = .000
YINTERCEPT = 1/(ALPHA*XMAX) = .000000
SLOPE OF BEST FIT = .000000
ALPHA = .000000
XMAX = .000000

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
1	11/06/69	.90000+08	.00000	.00000
2	11/07/69	.10000+09	.00000	.00000
3	11/07/69	.80000+08	.00000	.00000
4	11/07/69	.60000+08	.00000	.00000
5	11/07/69	.42000+08	.00000	.00000
6	11/07/69	.24000+08	.00000	.00000
7	11/15/69	.90000+08	.00000	.00000
8	11/15/69	.80000+08	.00000	.00000
9	11/15/69	.45000+08	.00000	.00000
11	11/15/69	.20000+08	.00000	.00000
12	11/16/69	.18500+09	.00000	.00000
13	11/16/69	.16000+09	.00000	.00000
14	11/16/69	.14500+09	.00000	.00000
15	11/16/69	.13000+09	.00000	.00000
16	11/16/69	.11800+09	.00000	.00000
17	11/22/69	.28000+09	.00000	.00000
18	11/22/69	.24000+09	.00000	.00000
19	11/22/69	.23000+09	.00000	.00000
20	11/22/69	.18000+09	.00000	.00000
21	11/22/69	.16000+09	.00000	.00000
22	11/22/69	.00000	.10000+03	.00000

Figure E-1. Analysis of equilibrium data, runs 1-22, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 10C.

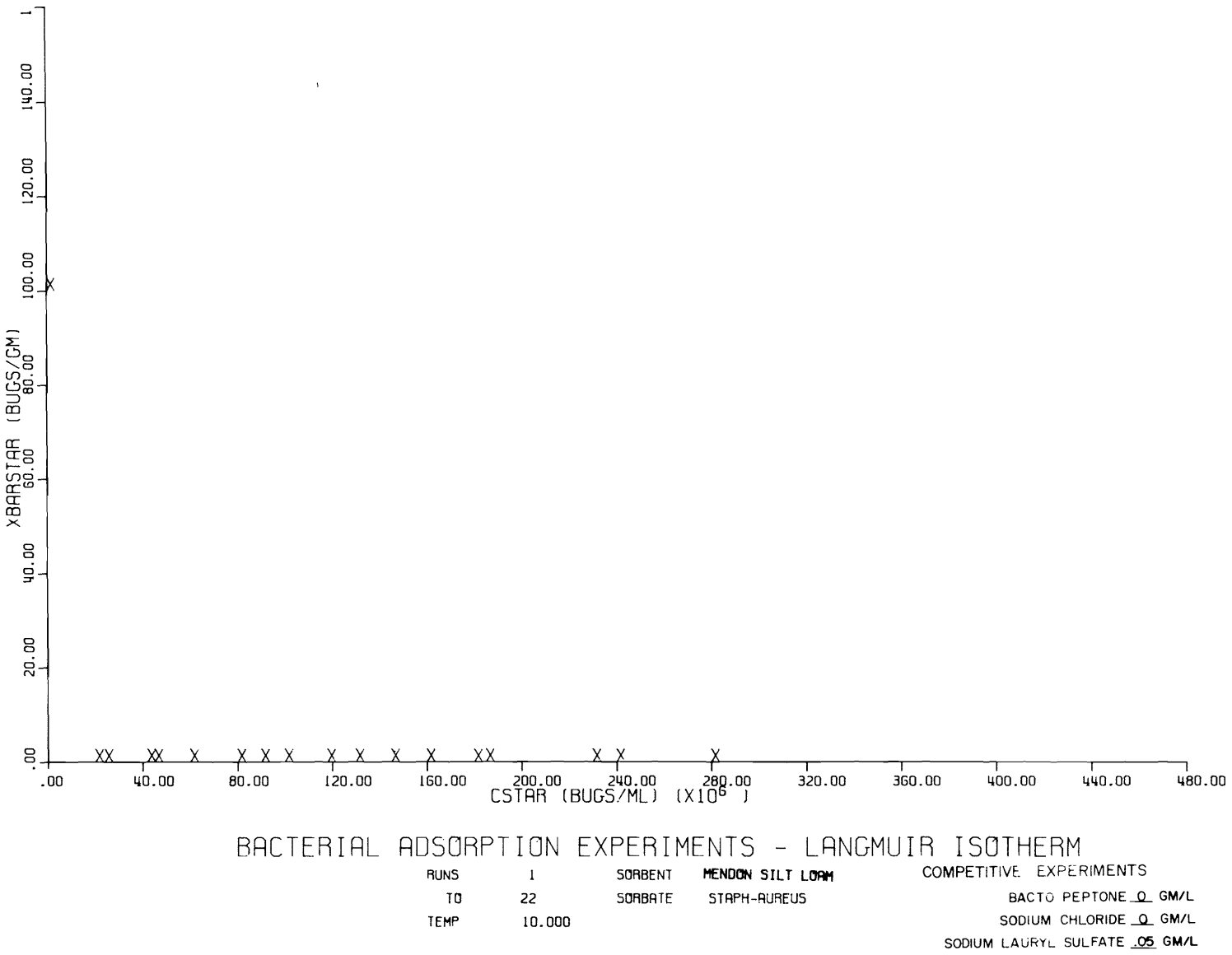


Figure E-2. Langmuir isotherm, runs 1-22, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 10C.

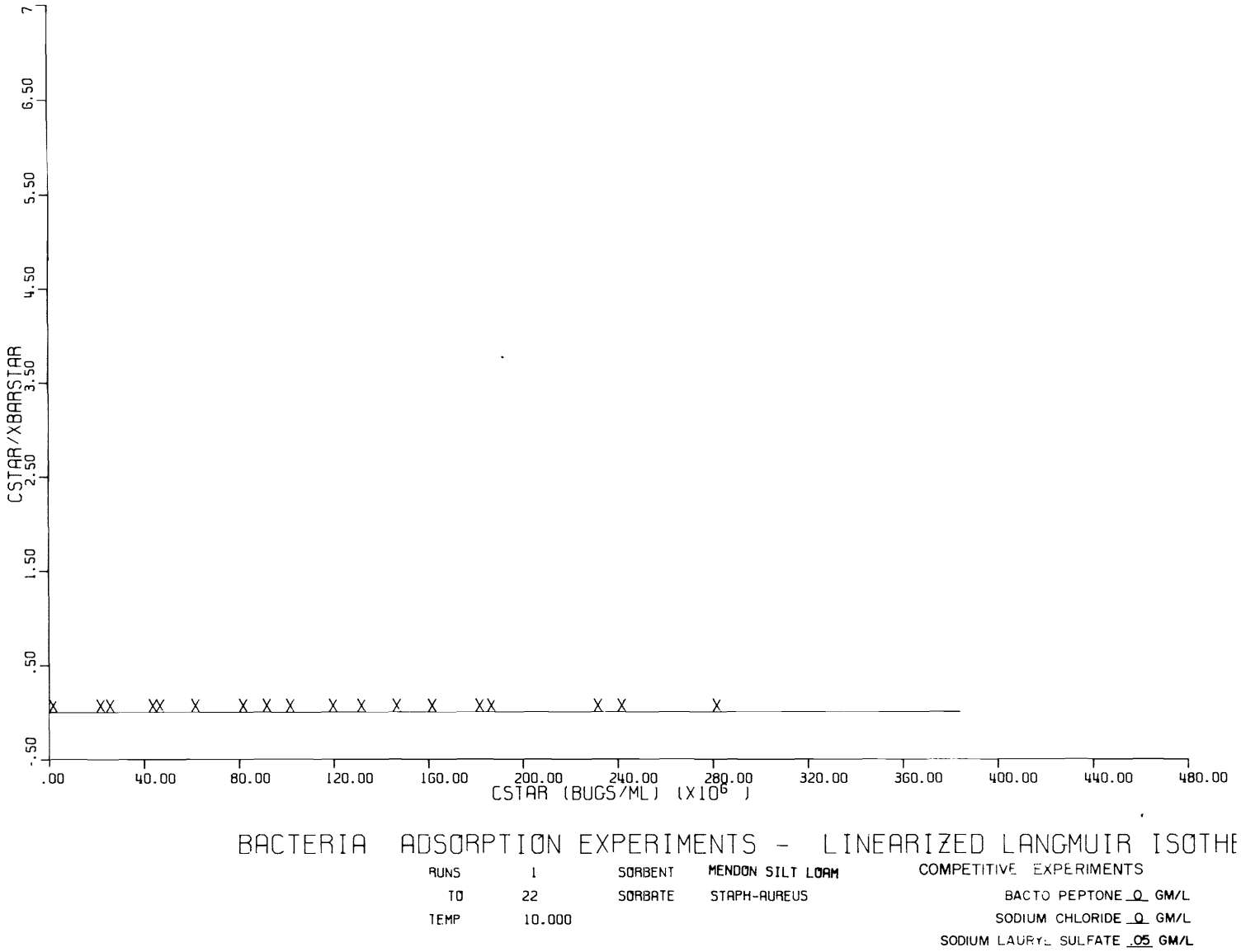


Figure E-3. Linearized Langmuir isotherm, runs 1-22, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 10C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 12/03/69
RUNS 1 TO 14

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM .01 LSG/L
TEMP 10.0 DEG. CENT.

PROGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .964
RSQ = .930
YINTERCEPT = 1/(ALPHA*XMAX) = .61975-63
SLOPE OF BEST FIT = .10927D-08
ALPHA = .17627E-05
XMAX = .91616+09

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
1	12/03/69	.15000+08	.90000+09	.16667-01
4	12/03/69	.50000+07	.67000+09	.74627-02
6	12/05/69	.18500+08	.75000+09	.24667-01
7	12/05/69	.22000+08	.85000+09	.25882-01
9	12/15/69	.28500+08	.85000+09	.33529-01
10	12/19/69	.95000+07	.85000+09	.11176-01
11	12/09/69	.13000+08	.90000+09	.14444-01
12	12/09/69	.15500+08	.10000+10	.15500-01
13	12/09/69	.28000+08	.10000+10	.29000-01
14	12/09/69	.27000+08	.10000+10	.27000-01
⊗ 2	12/03/69	.14000+08	.14000+10	.10000-01
⊗ 3	12/03/69	.13000+08	.18000+10	.72222-02
⊗ 5	12/05/69	.15000+08	.65000+09	.23077-01
⊗ 8	12/05/69	.25000+08	.70000+09	.35714-01

⊗ Deleted from regression analysis but plotted in Figures

Figure E-4. Analysis of equilibrium data, runs 1-14, *S. aureus* and Mendon silt loam and .01 gm/l SLS, 10C.

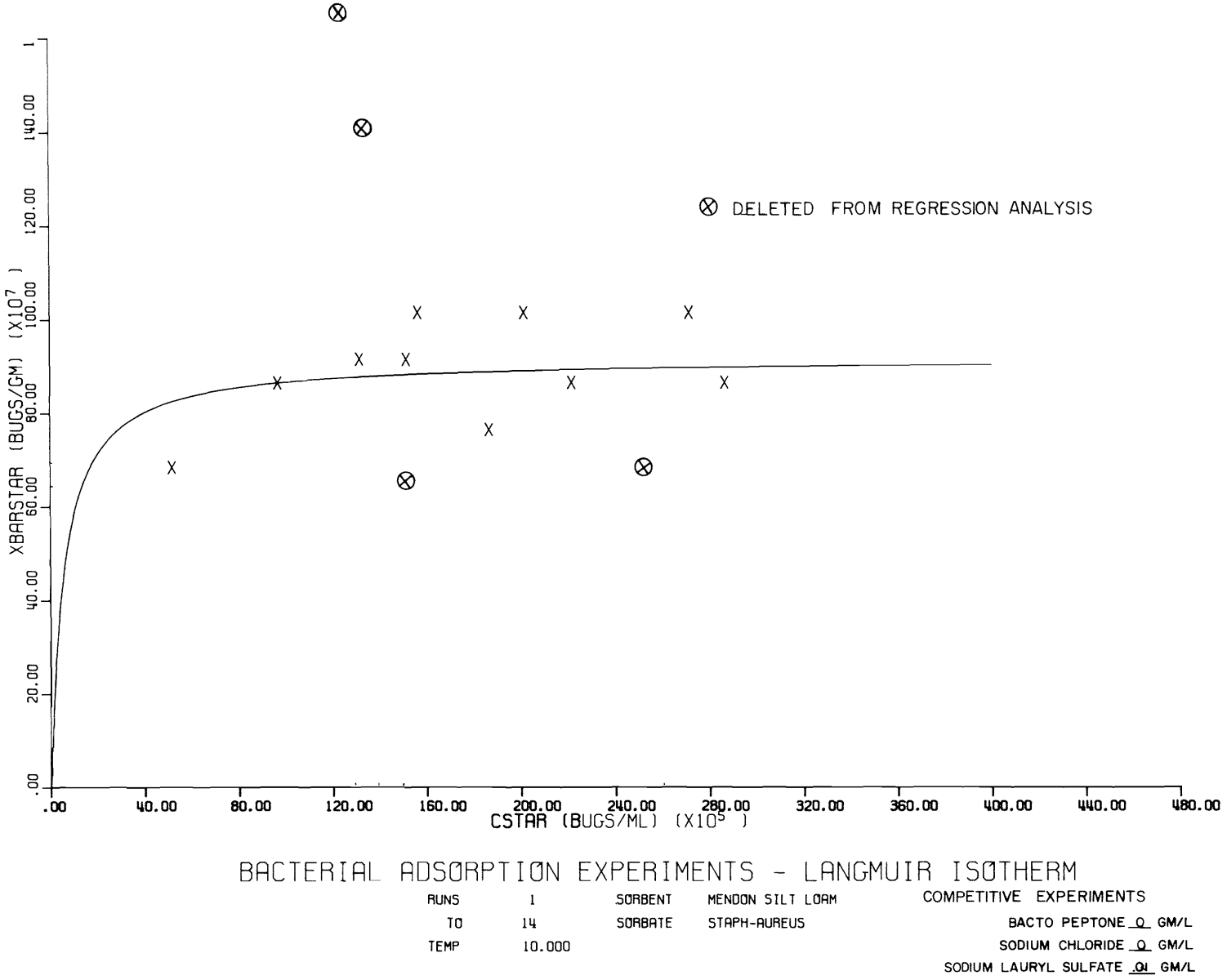


Figure E-5. Langmuir isotherm, runs 1-14, *S. aureus* and Mendon silt loam and .01 gm/l SLS, 10C.

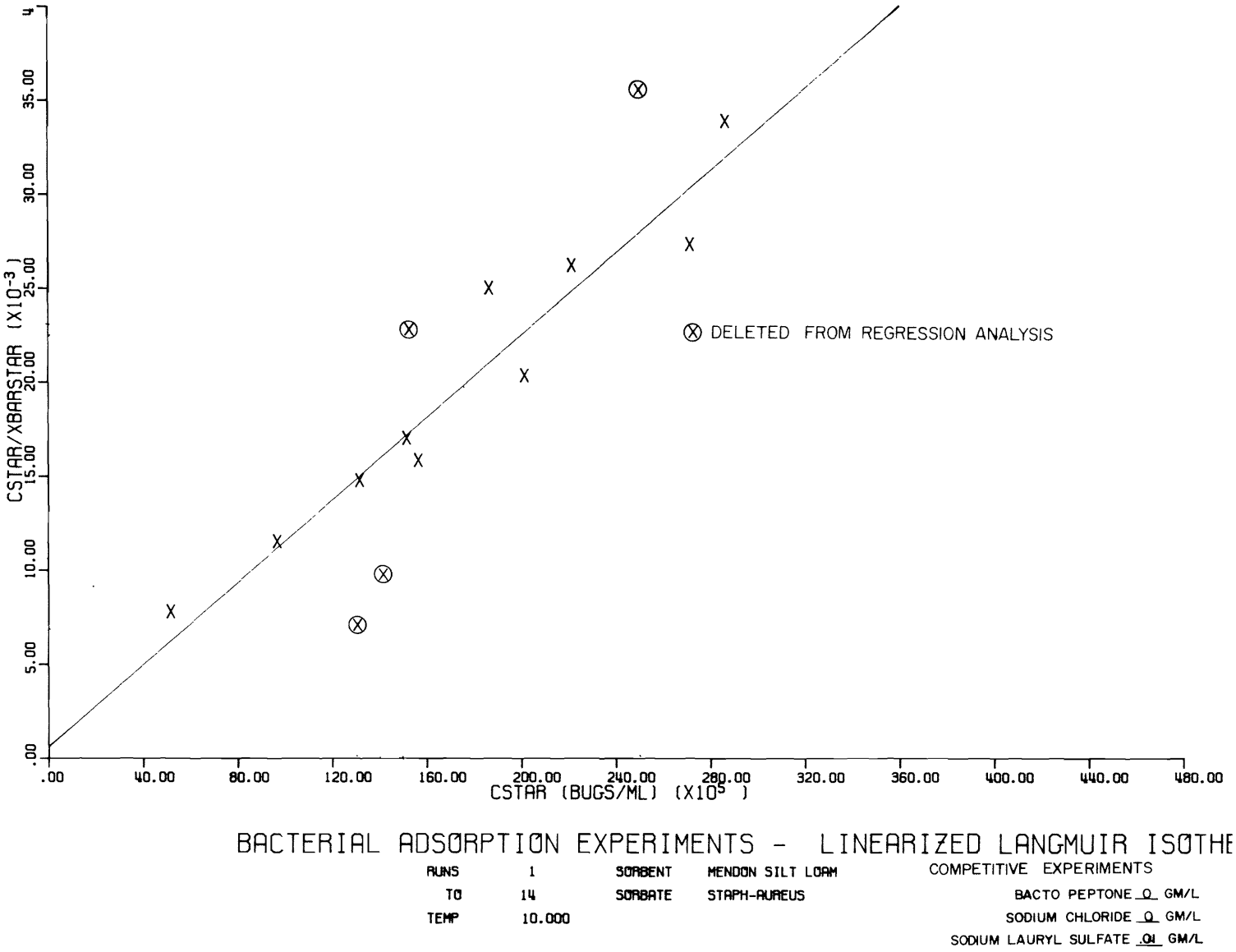


Figure E-6. Linearized Langmuir isotherm, runs 1-14, *S. aureus* and Mendon silt loam and .01 gm/l SLS, 10C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 02/40/70
RUNS 2 TO 14

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM 0.05LSG/L
TEMP 20.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .950
RSQ = .903
Y INTERCEPT = 1/(ALPHA*XMAX) = .268125-03
SLOPE OF BEST FIT = .949196-10
ALPHA = .354012-06
XMAX = .105352+11

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	02/40/70	.10000+09	.10000+11	.10000-01
3	02/07/70	.90000+08	.10600+11	.84906-02
4	02/04/70	.70000+08	.10000+11	.70000-02
5	02/04/70	.50000+08	.88000+10	.56818-02
7	02/05/70	.17000+09	.10000+11	.17000-01
8	02/05/70	.13500+09	.11000+11	.12273-01
9	02/05/70	.90000+08	.14000+11	.64286-02
10	02/05/70	.50000+08	.80000+10	.62500-02
12	02/06/70	.14000+09	.11000+11	.12727-01
13	02/06/70	.14000+09	.11000+11	.12727-01
13	02/06/70	.12500+09	.10000+11	.12500-01
14	02/06/70	.12000+09	.88000+10	.13636-01

Figure E-7. Analysis of equilibrium data, runs 2-14, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 20C.

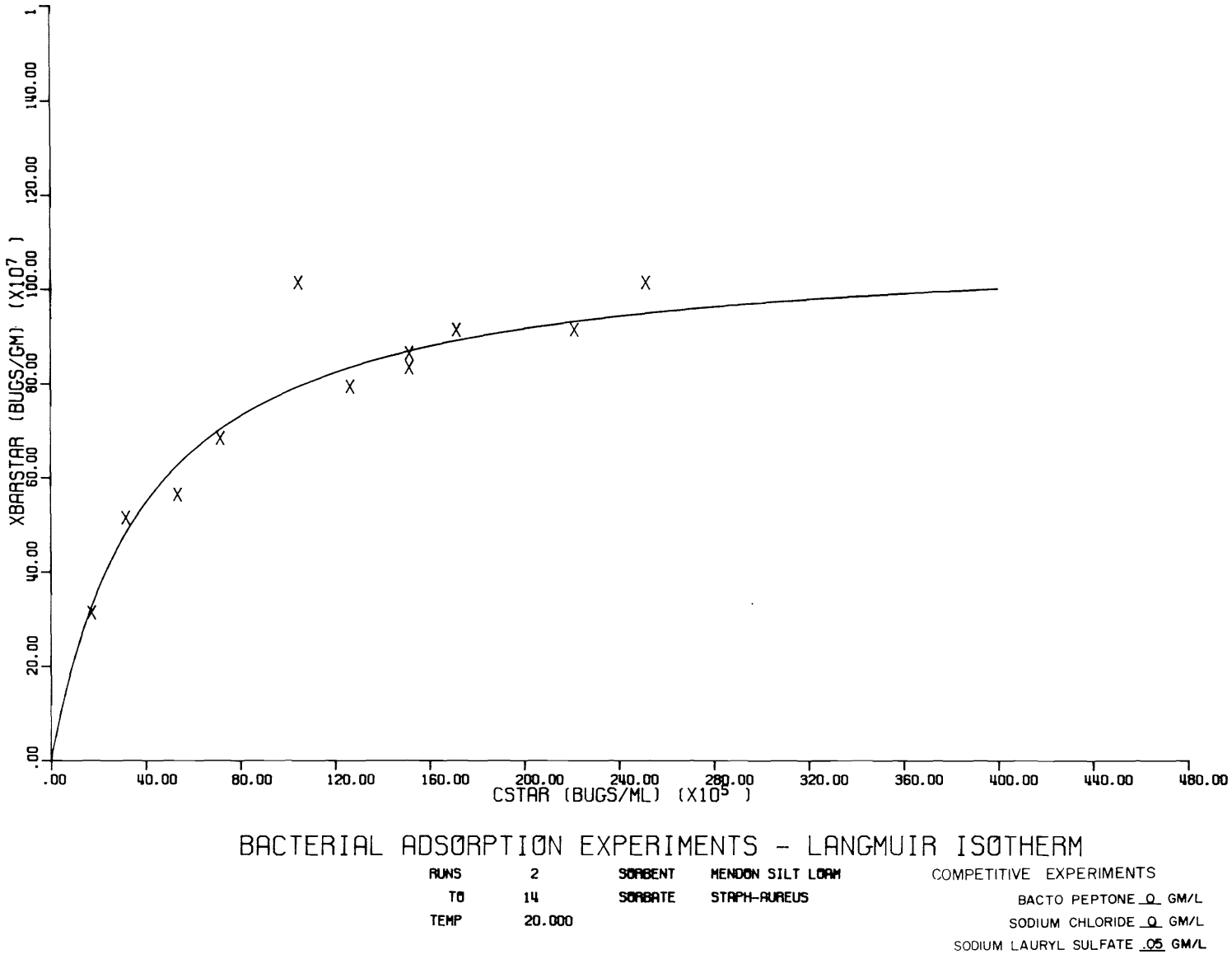


Figure E-8. Langmuir isotherm, runs 2-14, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 20C.

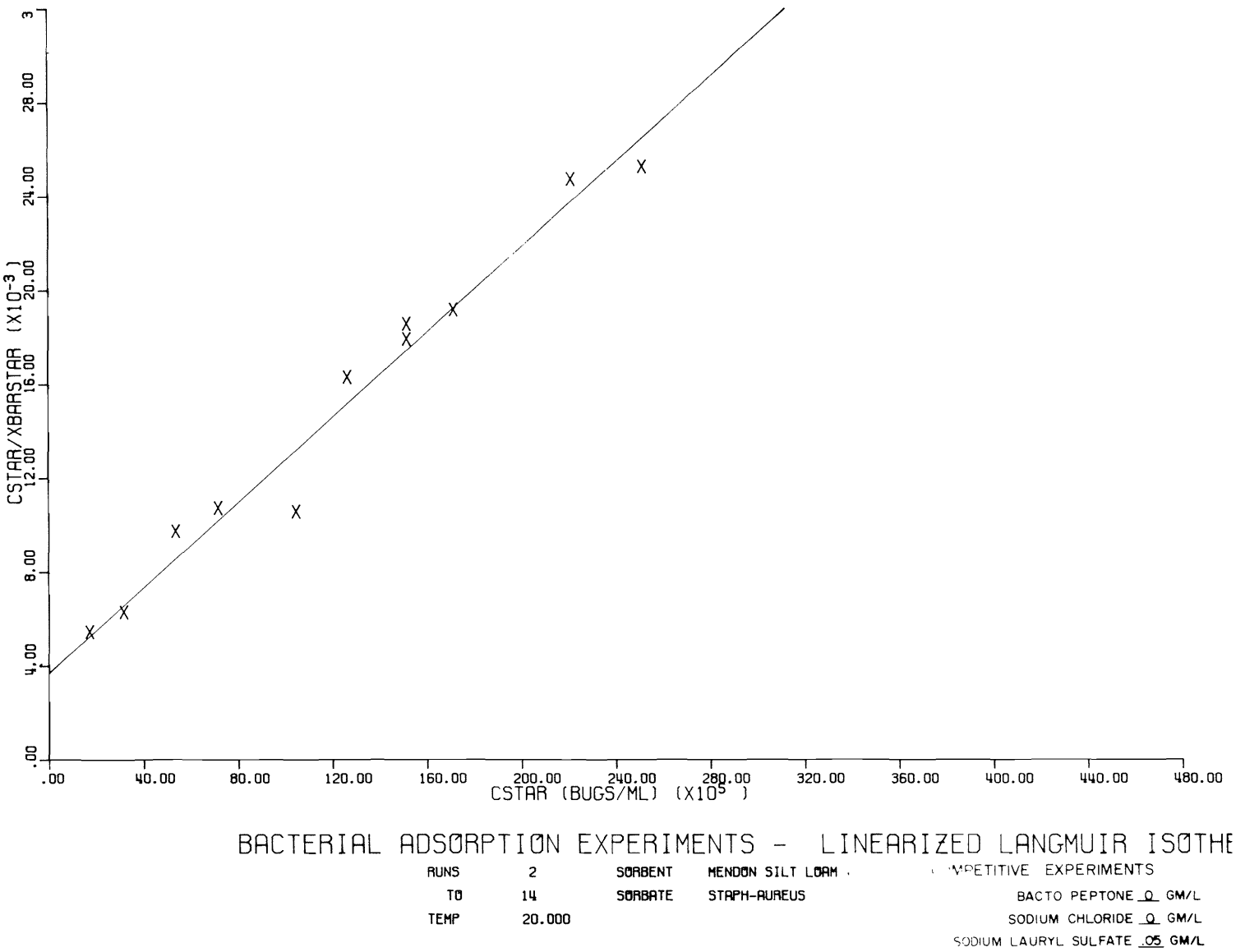


Figure E-9. Linearized Langmuir isotherm, runs 2-14, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 20C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 10/30/69
RUNS 2 TO 17

SORBATE STAPH-AUREUS
EDA-[illegible]
SORBENT MENDON SILT LOAM
.05 LSG/L
TEMP 27.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .999
RSQ = .997
Y INTERCEPT = 1/(ALPHA*XMAX) = .259390-03
SLOPE OF BEST FIT = .194452-09
ALPHA = .406296-06
XMAX = .913640+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

	RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
	2	10/30/69	.25000+08	.10000+11	.25000-01
	3	10/30/69	.21550+08	.11000+11	.19545-01
	4	10/30/69	.15000+08	.80000+10	.25000-01
	9	11/04/69	.14000+08	.11200+11	.12500-01
	10	11/04/69	.10000+09	.56000+10	.17857-01
	13	12/11/69	.14000+08	.12500+11	.11200-01
	14	12/11/69	.15000+08	.95000+10	.10526-01
	15	12/11/69	.80000+08	.95000+10	.84118-02
	16	12/11/69	.55000+08	.95000+10	.57895-02
	17	12/11/69	.35000+08	.81000+10	.43210-02
⊗	6	10/30/69	.10000 + 09	.13600 + 11	.73529 - 02
⊗	11	11/04/69	.73000 + 08	.10000 + 11	.73000 - 02

⊗ Deleted from regression analysis but plotted in Figures

Figure E-10. Analysis of equilibrium data, runs 2-17, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 27C.

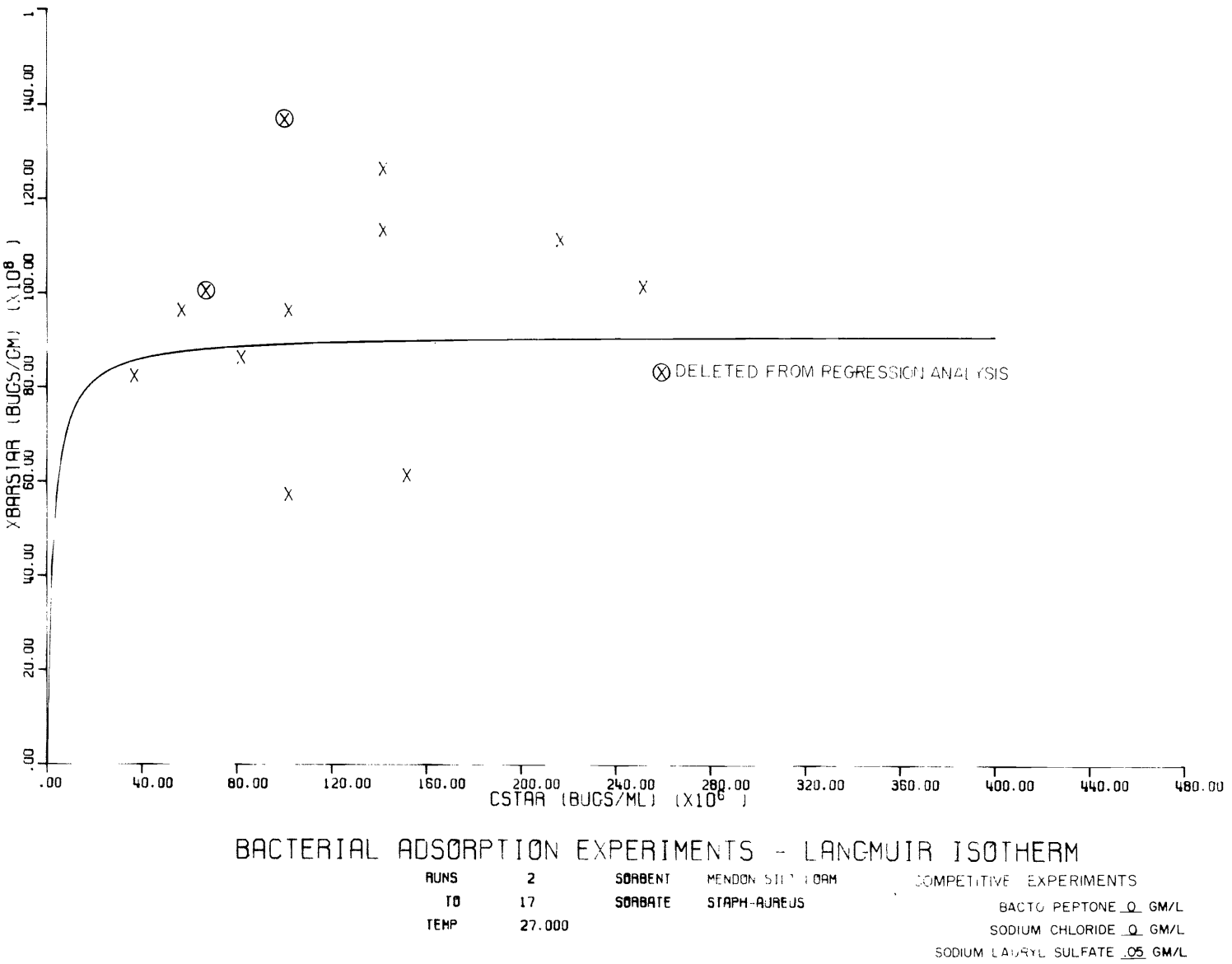


Figure E-11. Langmuir isotherm, runs 2-17, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 27C.

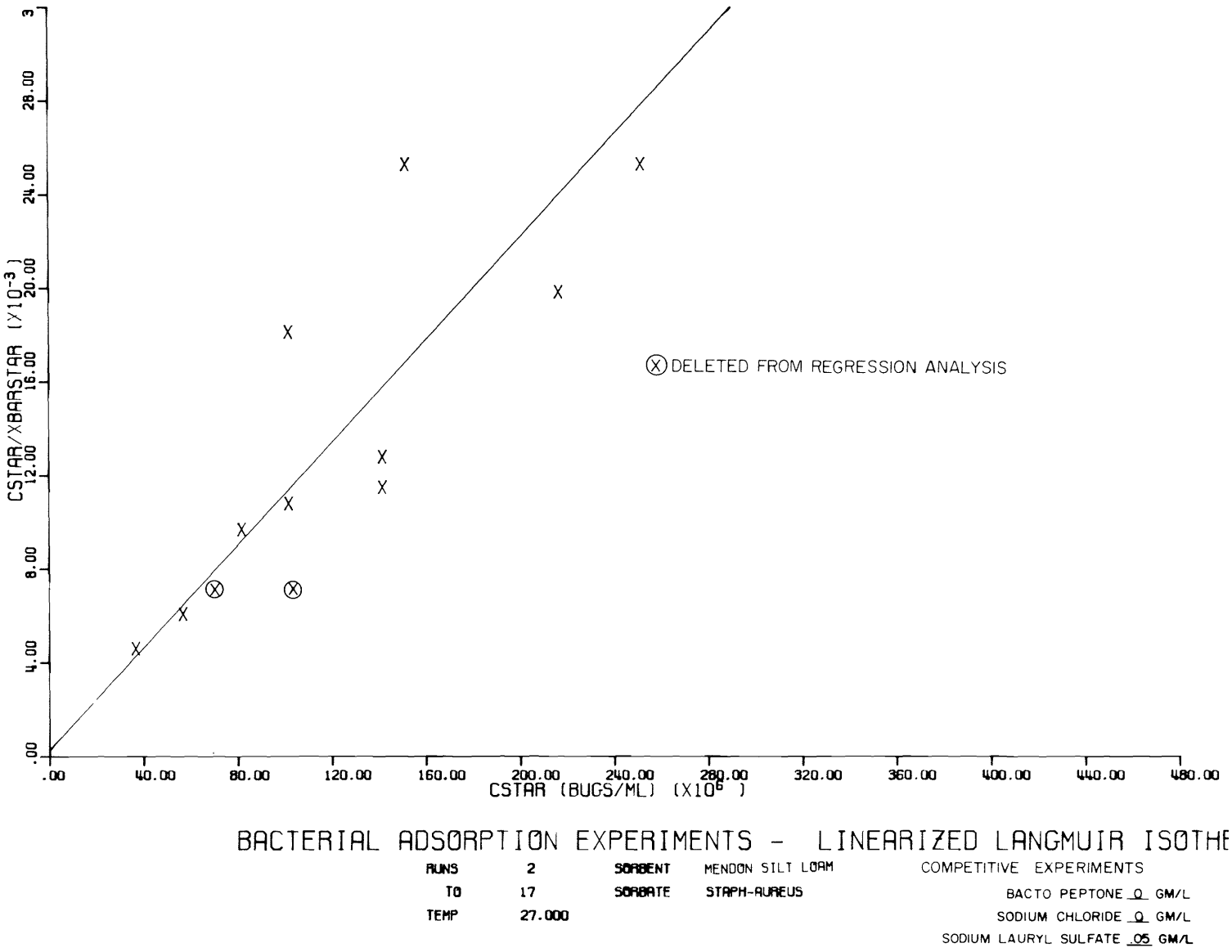


Figure E-12. Linearized Langmuir isotherm, runs 2-17, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 27C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 01/15/70
RUNS 7 TO 15

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM 0.05LSG/L
TEMP 37.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .945
RSQ = .892
YINTERCEPT = 1/(ALPHA*XMAX) = .142863-03
SLOPE OF BEST FIT = .650890-10
ALPHA = .455606-06
XMAX = .153636+11

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
7	01/15/70	.50000+08	.16000+11	.31250-02
8	01/15/70	.50000+08	.12500+11	.40000-02
9	01/15/70	.60000+08	.18000+11	.33333-02
10	01/15/70	.58000+08	.16000+11	.36250-02
11	01/15/70	.70000+08	.14000+11	.50000-02
13	03/12/70	.10000+08	.11500+11	.86957-03
14	03/12/70	.30000+08	.13500+11	.22222-02
15	03/12/70	.50000+08	.14000+11	.35714-02

Figure E-13. Analysis of equilibrium data, runs 7-15, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 37C.

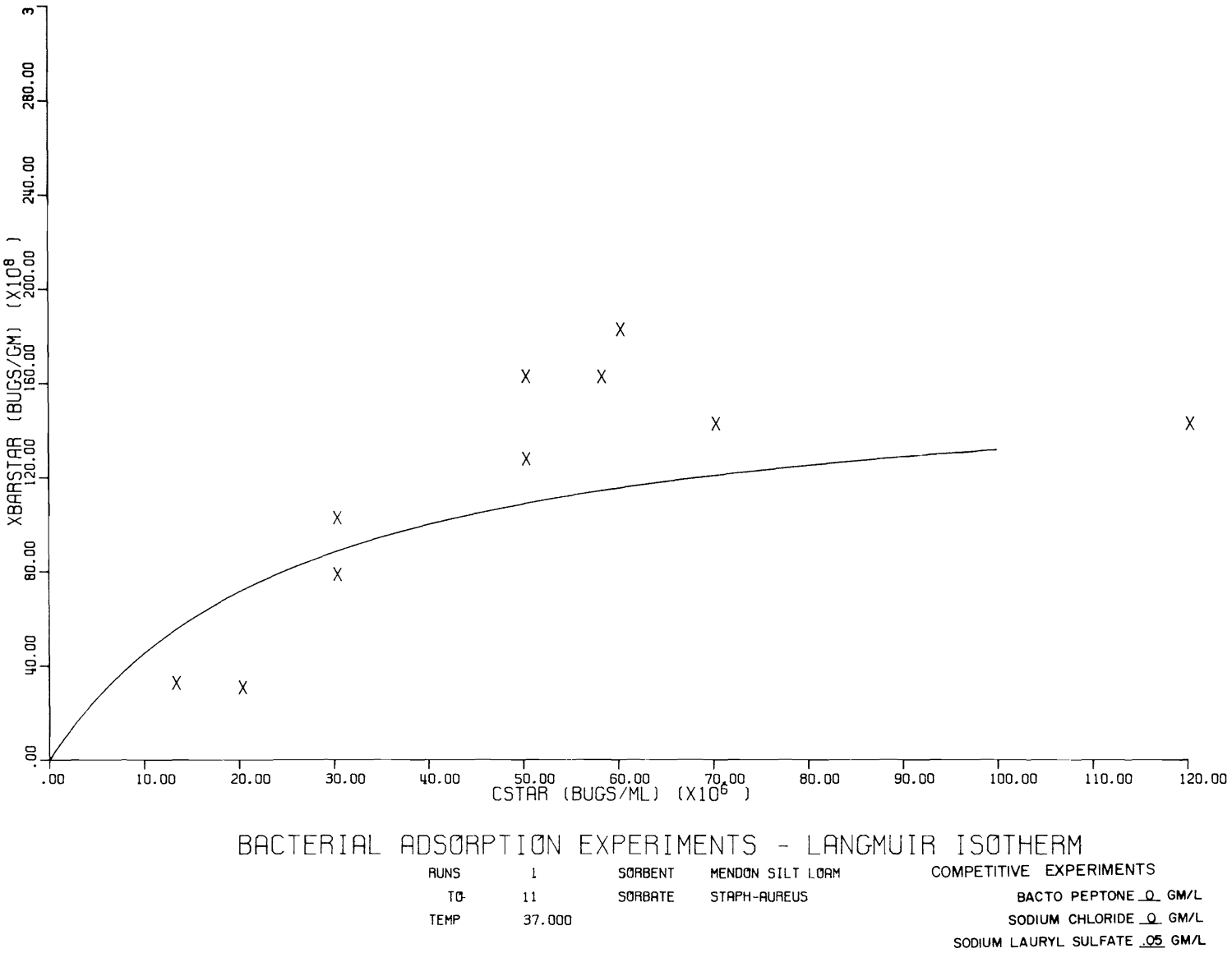


Figure E-14. Langmuir isotherm, runs 7-15, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 37C.

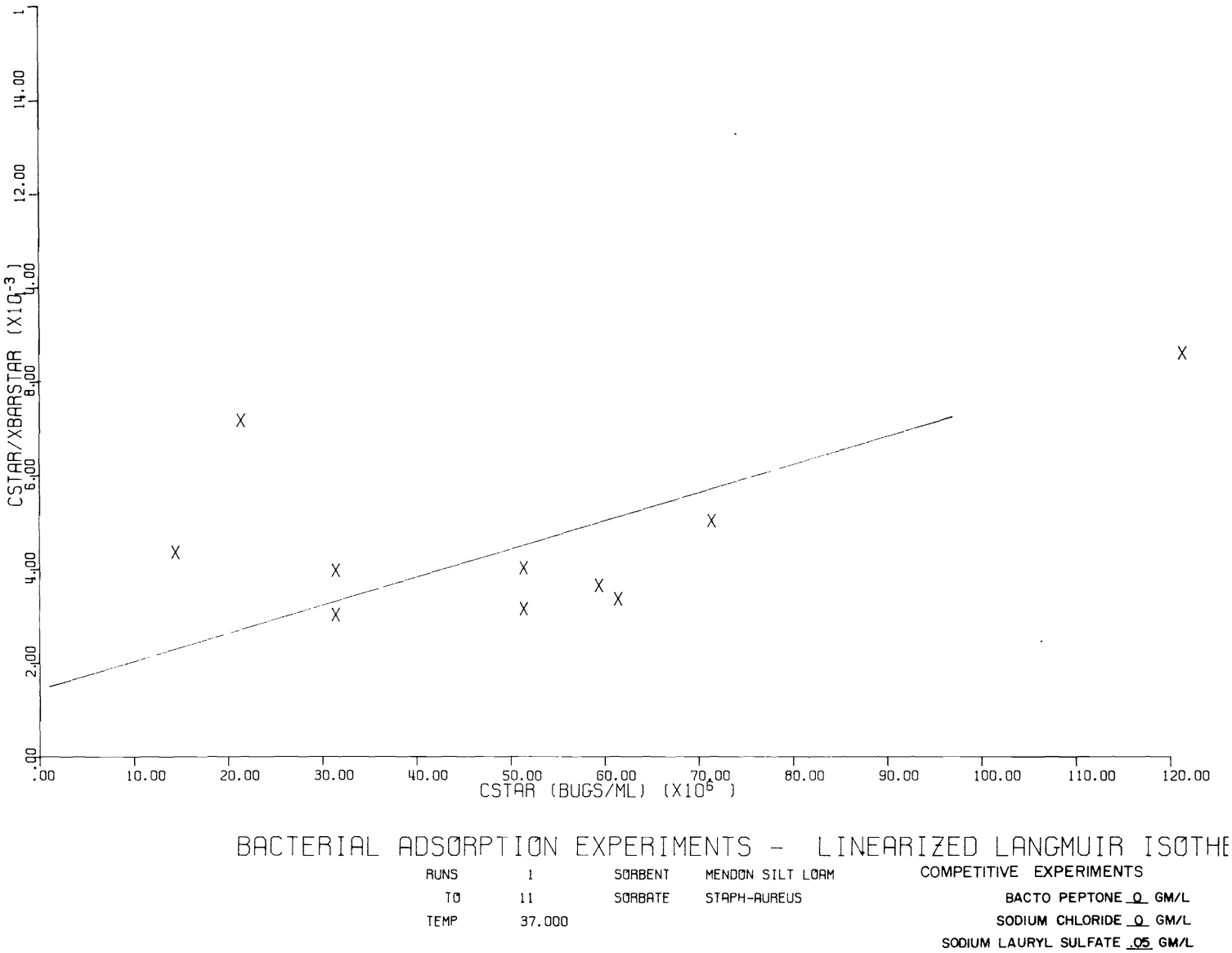


Figure E-15. Linearized Langmuir isotherm, runs 7-15, *S. aureus* and Mendon silt loam and .05 gm/l SLS, 37C.

APPENDIX F

BACTERIAL ADSORPTION ISOTHERMS (WITH PEPTONE COMPETITION)

Bacto-Peptone 3.8 gm/l
Sodium Chloride 0 gm/l
Sodium Lauryl Sulfate 0 gm/l

Bacterial uptake isotherms using peptone (3.8 grams per liter) as a competitive sorbate are shown in this appendix. Results of these isotherms are summarized in Table 2.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 12/10/69
RUNS 2 TO 21

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM
3.8GPEPTONE/L
TEMP 10.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .[illegible]
RSQ = .[illegible]
YINTERCEPT = 1/(ALPHA*XMAX) = .[illegible]
SLOPE OF BEST FIT = .[illegible]
ALPHA = .[illegible]
XMAX = .[illegible]

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	12/10/69	.1900E+08	.0000	.0000
3	12/10/69	.1400E+08	.0000	.0000
4	12/10/69	.1600E+08	.0000	.0000
5	12/10/69	.2600E+08	.0000	.0000
12	12/16/69	.5500E+07	.0000	.0000
14	12/16/69	.1230E+08	.0000	.0000
15	12/16/69	.1570E+08	.0000	.0000
17	12/18/69	.7500E+07	.0000	.0000
18	12/18/69	.9700E+07	.0000	.0000
19	12/18/69	.1150E+08	.0000	.0000
20	12/18/69	.1650E+08	.0000	.0000
21	12/18/69	.0000	.1080E+04	.0000

Figure F-1. Analysis of equilibrium data, runs 2-21, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 10C.

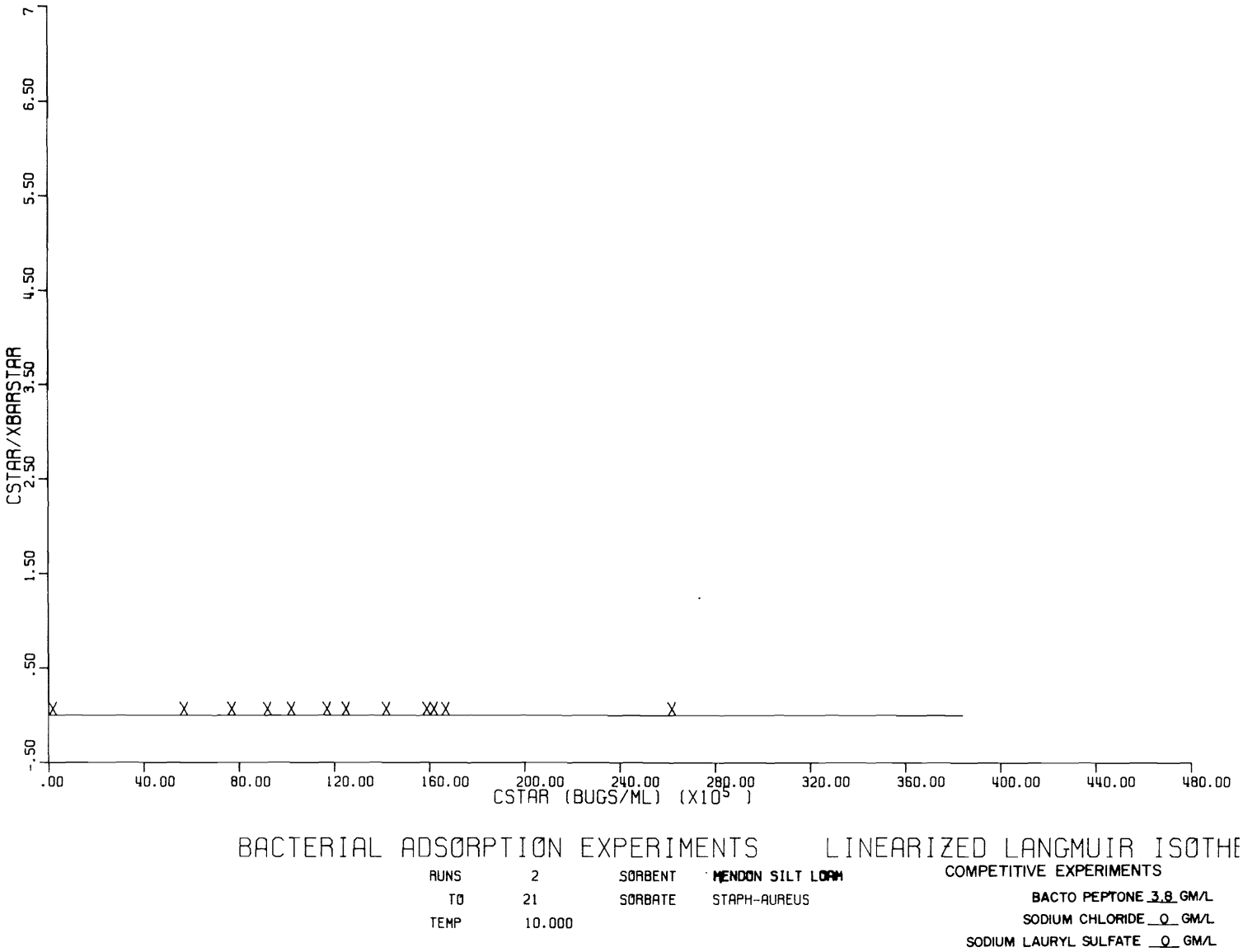


Figure F-2. Langmuir isotherm, runs 2-21, *S. aureus* and Mendon silt loam 3.8 gm/l peptone, 10C.

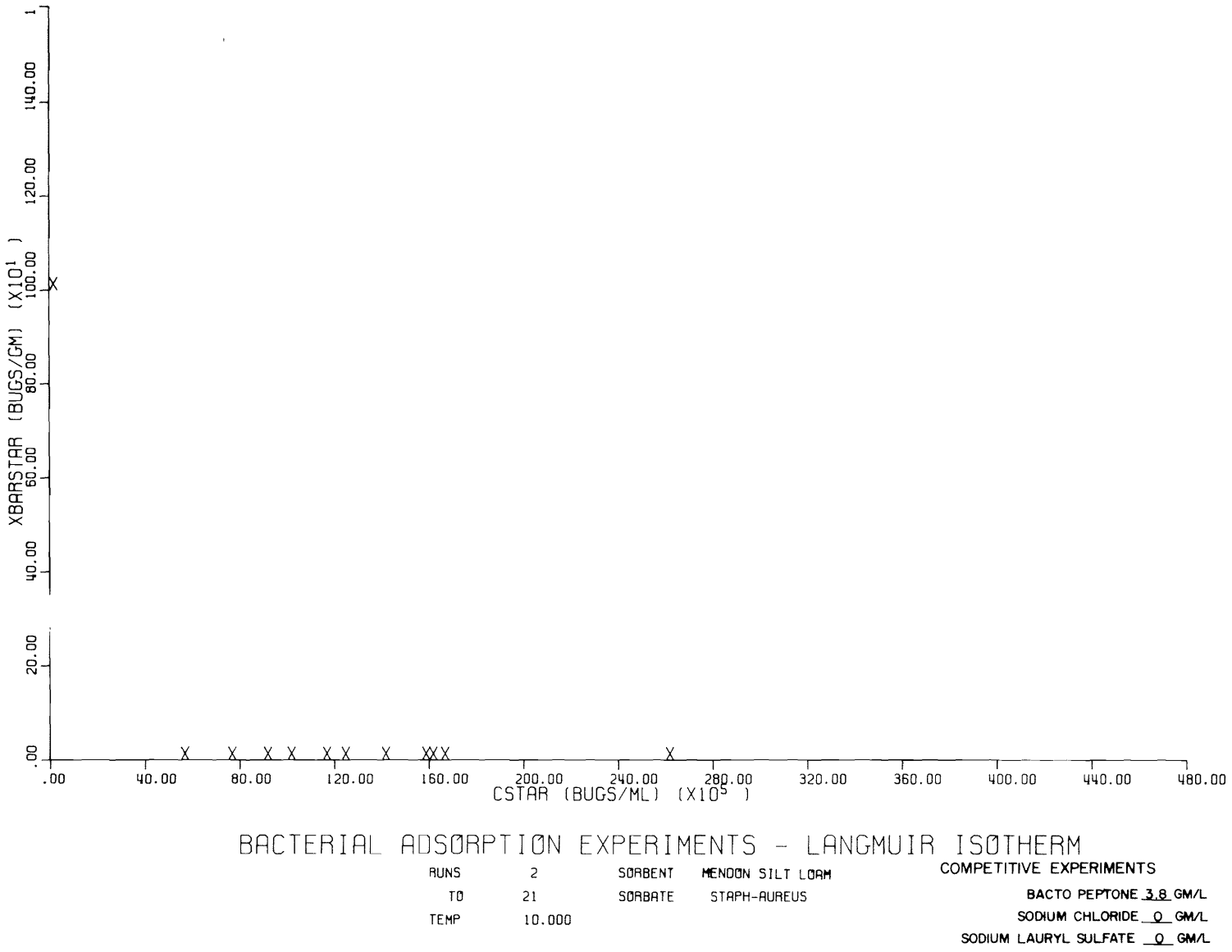


Figure F-3. Linearized Langmuir isotherm, runs 2-21, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 10C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 02/08/70
RUNS 2 TO 14

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM 3.8GPEPTONE/L
TEMP 20.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .986
RSQ = .972
Y INTERCEPT = 1/(ALPHA*XMAX) = .363309-02
SLOPE OF BEST FIT = .306355-09
ALPHA = .245420-06
XMAX = .110332+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	02/08/70	.52000+07	.55000+09	.94545-02
3	02/08/70	.30000+07	.50000+09	.60000-02
4	02/08/70	.15500+07	.30000+09	.51667-02
6	02/10/70	.17000+08	.30000+09	.18889-01
7	02/10/70	.15000+08	.82000+09	.18293-01
8	02/10/70	.12500+08	.78000+09	.16026-01
9	02/10/70	.70000+07	.67000+09	.10448-01
11	02/12/70	.10300+08	.10000+10	.10300-01
12	02/12/70	.15000+08	.85000+09	.17647-01
13	02/12/70	.22000+08	.90000+09	.24444-01
14	02/12/70	.25000+08	.10000+10	.25000-01

Figure F-4. Analysis of equilibrium data, runs 2-14, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 20C.

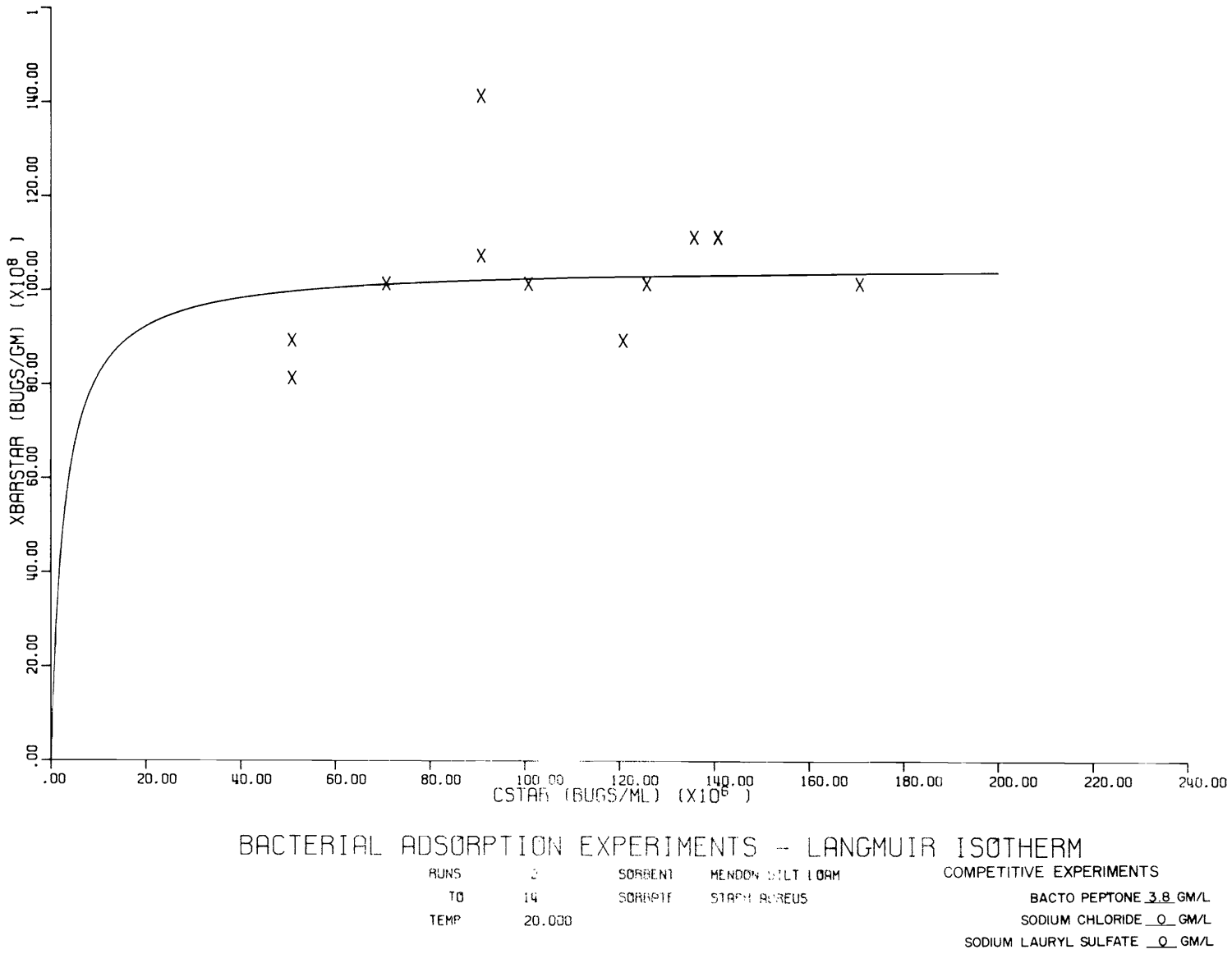


Figure F-5. Langmuir isotherm, runs 2-14, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 20C.

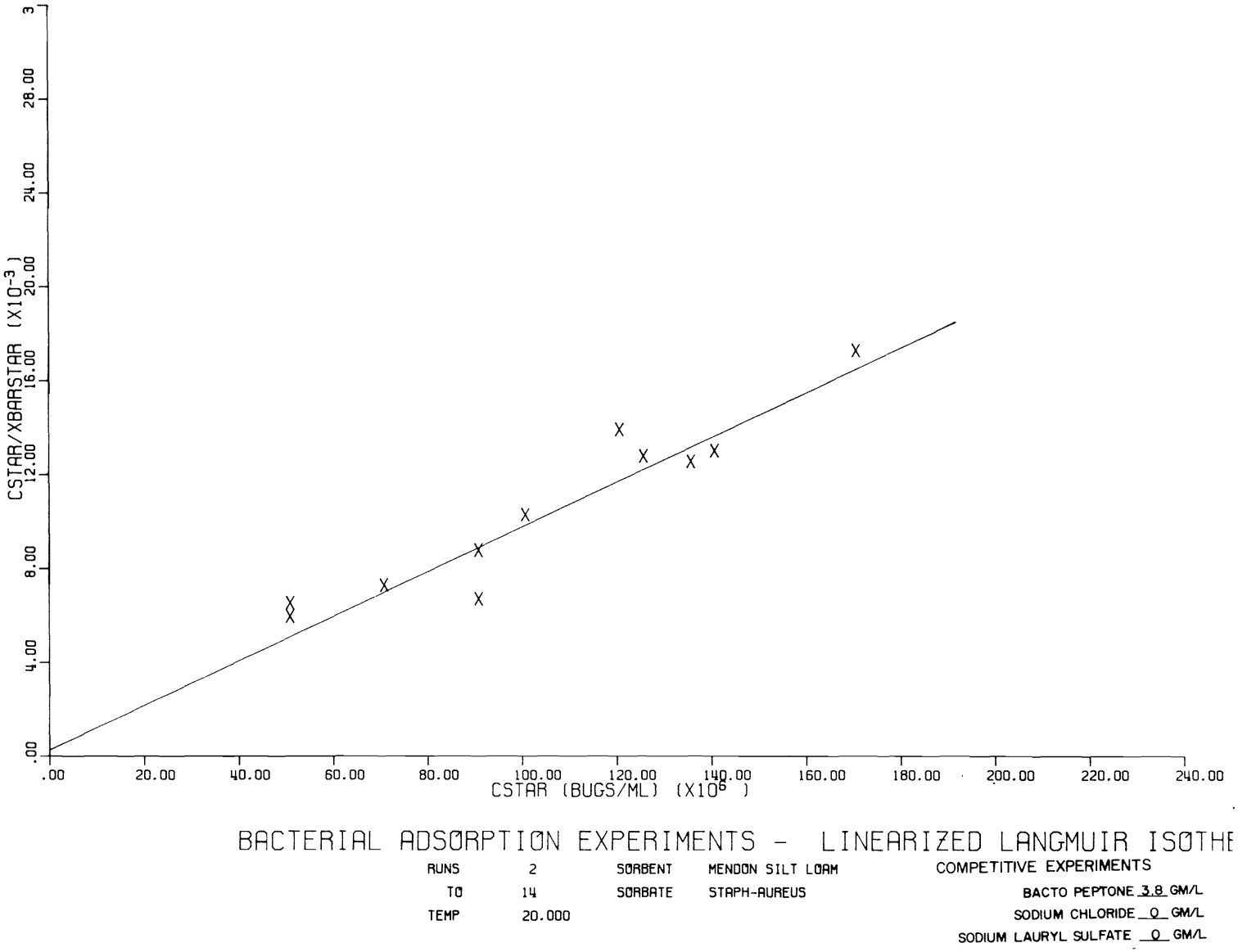


Figure F-6. Linearized Langmuir isotherm, runs 2-14, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 20C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 12/02/69
RUNS 2 TO 15

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM 3.8GPEPTONE/L
TEMP 27.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .879
RSQ = .772
YINTERCEPT = 1/(ALPHA*XMAX) = .410571-02
SLOPE OF BEST FIT = .488661-09
ALPHA = .119020-06
XMAX = .204641+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	12/02/69	.80000+07	.83000+09	.96386-02
3	12/02/69	.53000+07	.75000+09	.70667-02
4	12/05/69	.40000+07	.67000+09	.59701-02
5	12/02/69	.30000+07	.40000+09	.75000-02
7	12/04/69	.13500+08	.13000+10	.10385-01
8	12/04/69	.17000+08	.15500+10	.10968-01
9	12/04/69	.22000+08	.16000+10	.13750-01
10	12/04/69	.26000+08	.18000+10	.14444-01
12	12/06/69	.12000+08	.16000+10	.75000-02
13	12/06/69	.14000+08	.14000+10	.10000-01
14	12/06/69	.17500+08	.12500+10	.14000-01
15	12/06/69	.22000+08	.12000+10	.18333-01

Figure F-7. Analysis of equilibrium data, runs 2-15, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 27C.

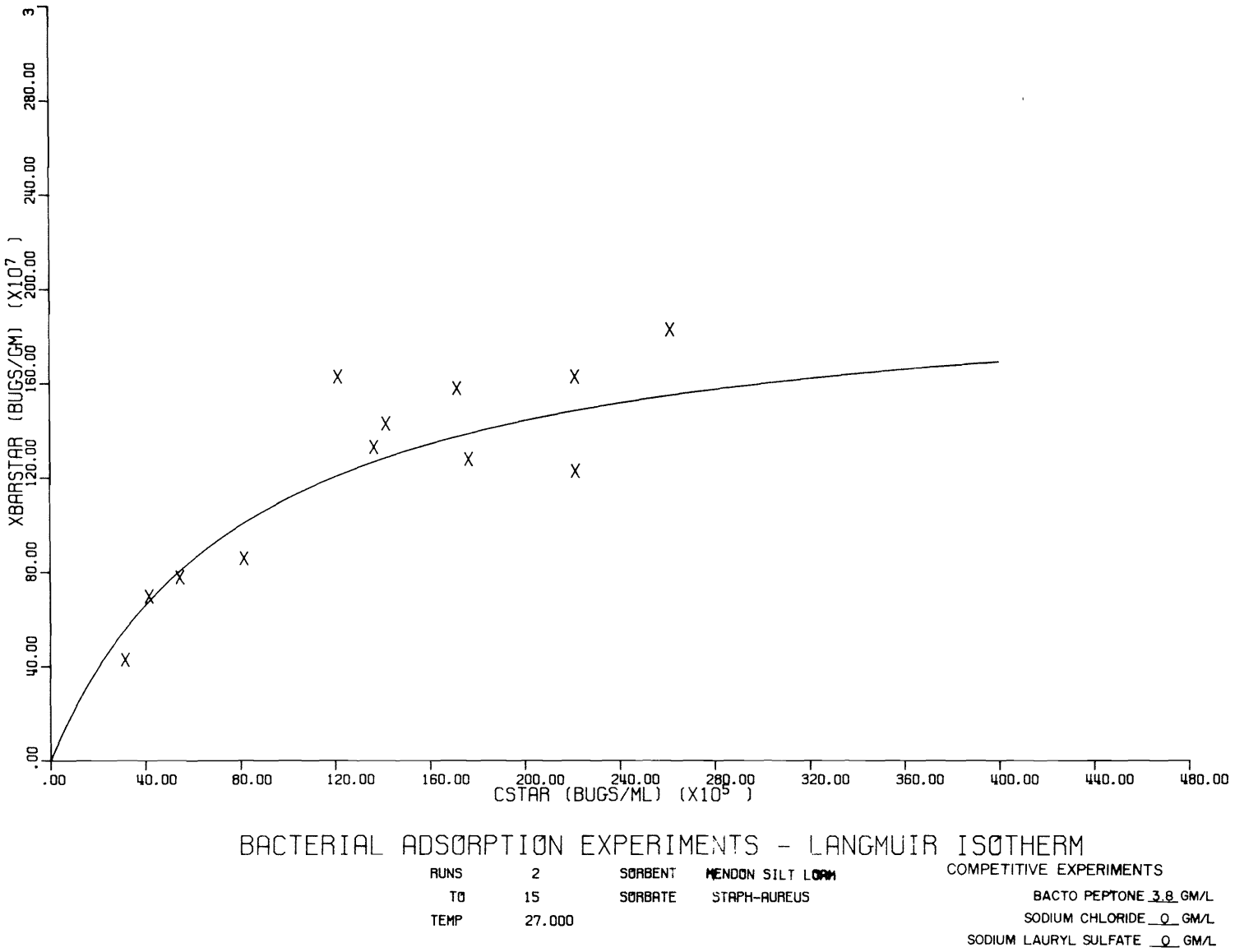


Figure F-8. Langmuir isotherm, runs 2-15, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 27C.

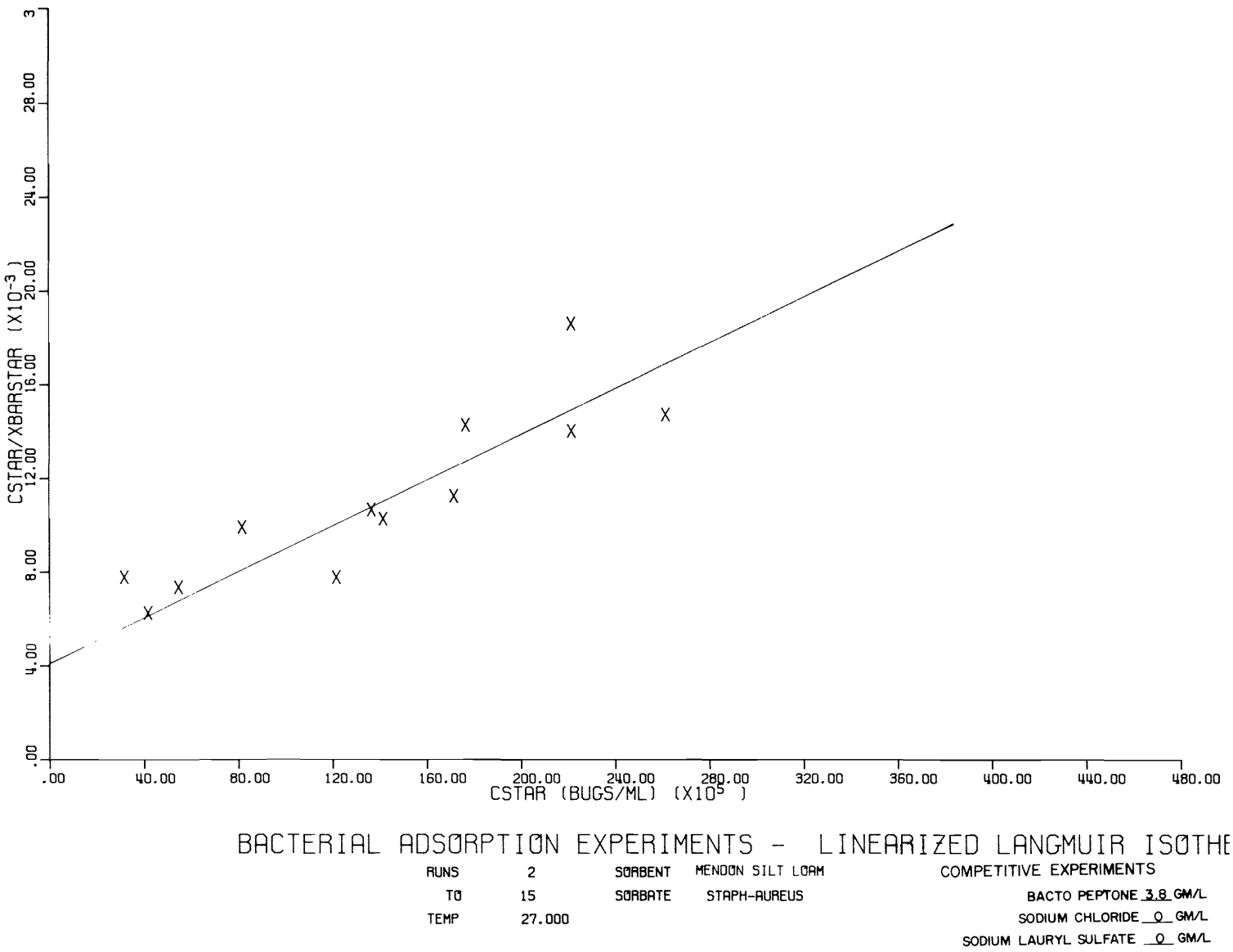


Figure F-9. Linearized Langmuir isotherm, runs 2-15, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 27C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 01/07170 SORBATE STAPH-AUREUS
RUNS 4 TO 19 FDA-209
SORBENT MENDON SILT LOAM
3.8GPEPTONE/L
TEMP 37.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .993
RSQ = .985
YINTERCEPT = 1/(ALPHA*XMAX) = .992122-03
SLOPE OF BEST FIT = .760797-09
ALPHA = .762229-06
XMAX = .131441+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	X/M*	C*/X/M*
4	01/07170	.26000+08	.12500+10	.20800-01
5	01/0717	.25000+08	.12000+10	.20833-01
8	01/09/70	.10000+08	.13500+10	.74074-02
9	01/09/70	.12000+08	.12500+10	.96000-02
10	01/09/70	.12500+08	.12500+10	.10000-01
12	01/14/70	.12000+08	.12000+10	.10000-01
13	01/14/70	.13500+08	.12500+10	.10800-01
14	01/14/70	.16000+08	.13000+10	.12308-01
15	01/14/70	.20000+08	.12000+10	.16667-01
16	02/26/70	.15000+07	.67000+09	.22389-02
17	02/26/70	.30000+07	.83000+09	.36145-02
18	02/26/70	.50000+07	.82000+09	.60976-02
19	02/26/7	.70000+07	.10000+10	.70000-0

Figure F-10. Analysis of equilibrium data, runs 4-19, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 37C.

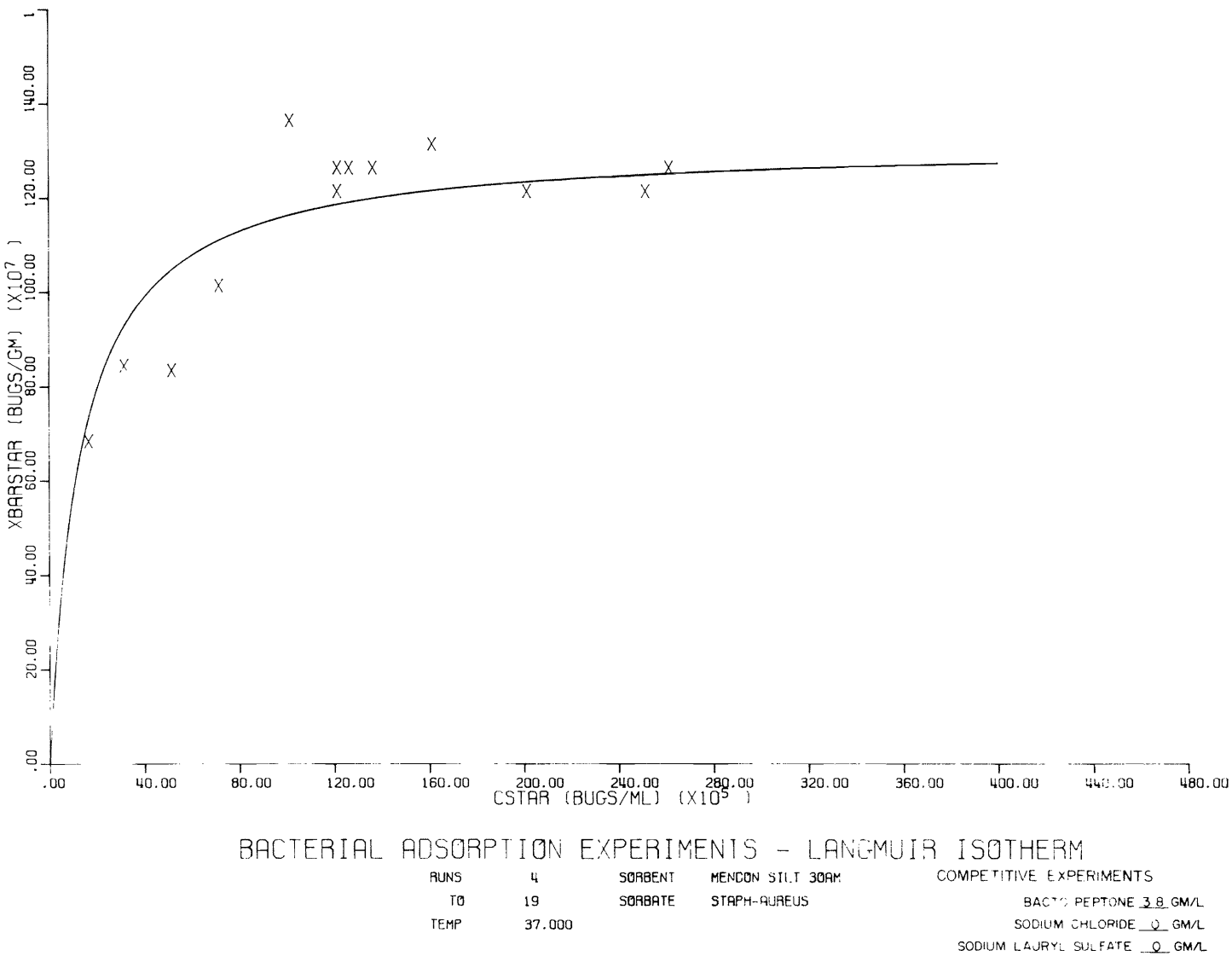


Figure F-11. Langmuir isotherm, runs 4-19, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 37C.

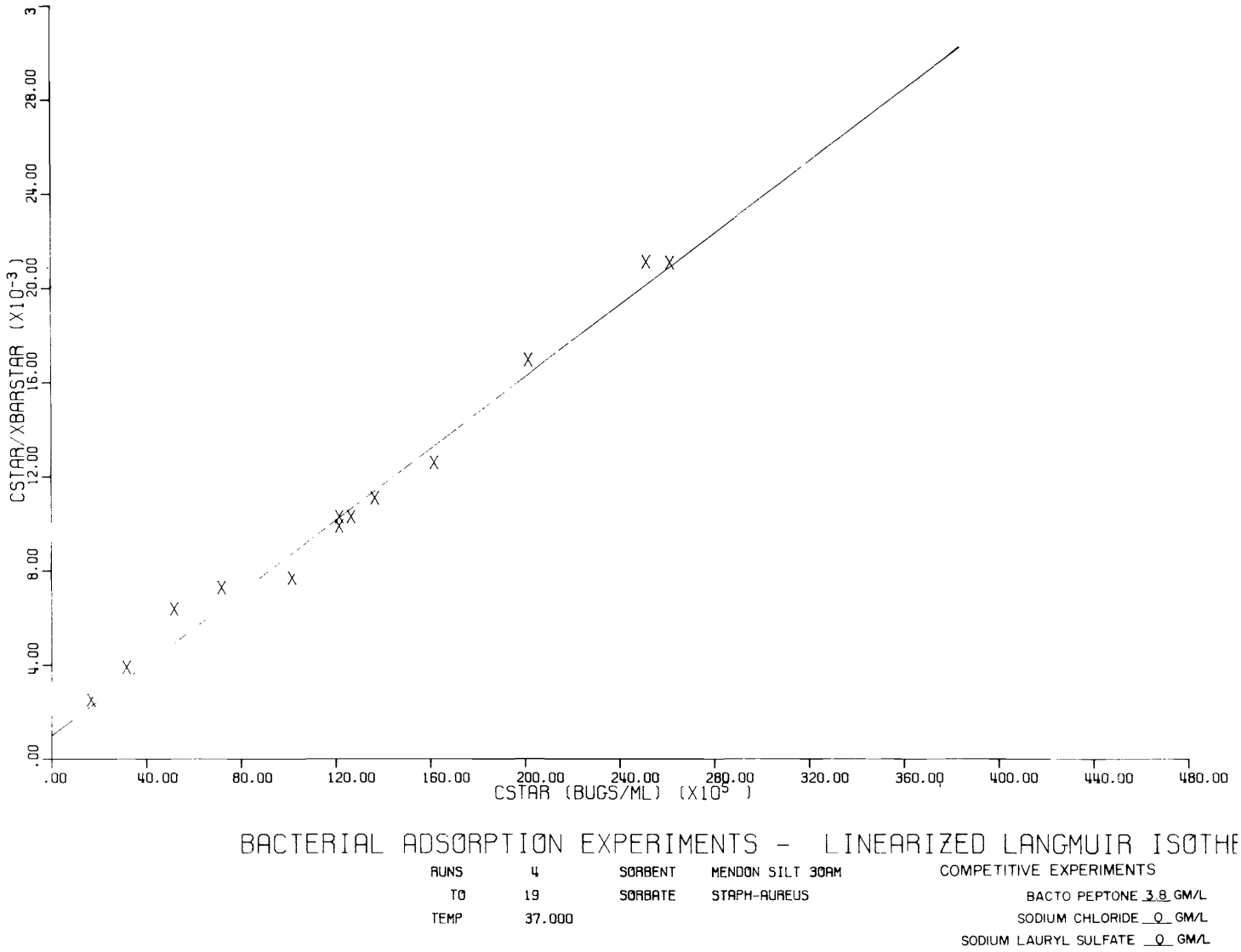


Figure F-12. Linearized Langmuir isotherm, runs 4-19, *S. aureus* and Mendon silt loam and 3.8 gm/l peptone, 37C.

APPENDIX G

BACTERIAL ADSORPTION ISOTHERMS (WITH NaCl COMPETITION)

Bacto-Peptone 0 gm/l
Sodium Chloride 30 gm/l
Sodium Lauryl Sulfate 0 gm/l

This appendix includes the isotherms obtained at 10C, 20C, 27C, and 37C, using NaCl (30 grams per liter) as a competitive sorbate. The summary of results of these isotherms is shown in Table 2.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 11/05/69
RUNS 2 TO 12

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM 3PCTNACL
TEMP 10.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .737
RSQ = .543
YINTERCEPT = 1/(ALPHA*XMAX) = .805940-02
SLOPE OF BEST FIT = .419580-10
ALPHA = .520E10-08
XMAX = .238334+11

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	11/05/69	.18000+09	.12000+11	.15000-01
3	11/05/69	.16000+09	.13300+11	.12030-01
4	11/05/69	.14000+09	.11000+11	.12727-01
5	11/05/69	.11000+09	.90000+10	.12222-01
6	11/05/69	.10800+09	.68000+10	.15882-01
8	11/07/69	.60000+08	.54000+10	.11111-01
9	11/07/69	.40000+08	.46000+10	.86957-02
10	11/07/69	.28000+08	.34000+10	.82353-02
11	11/07/69	.18000+08	.15000+10	.12000-01
12	11/07/69	.55000+07	.66000+09	.83333-02

Figure G-1. Analysis of equilibrium data, runs 2-12, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 10C.

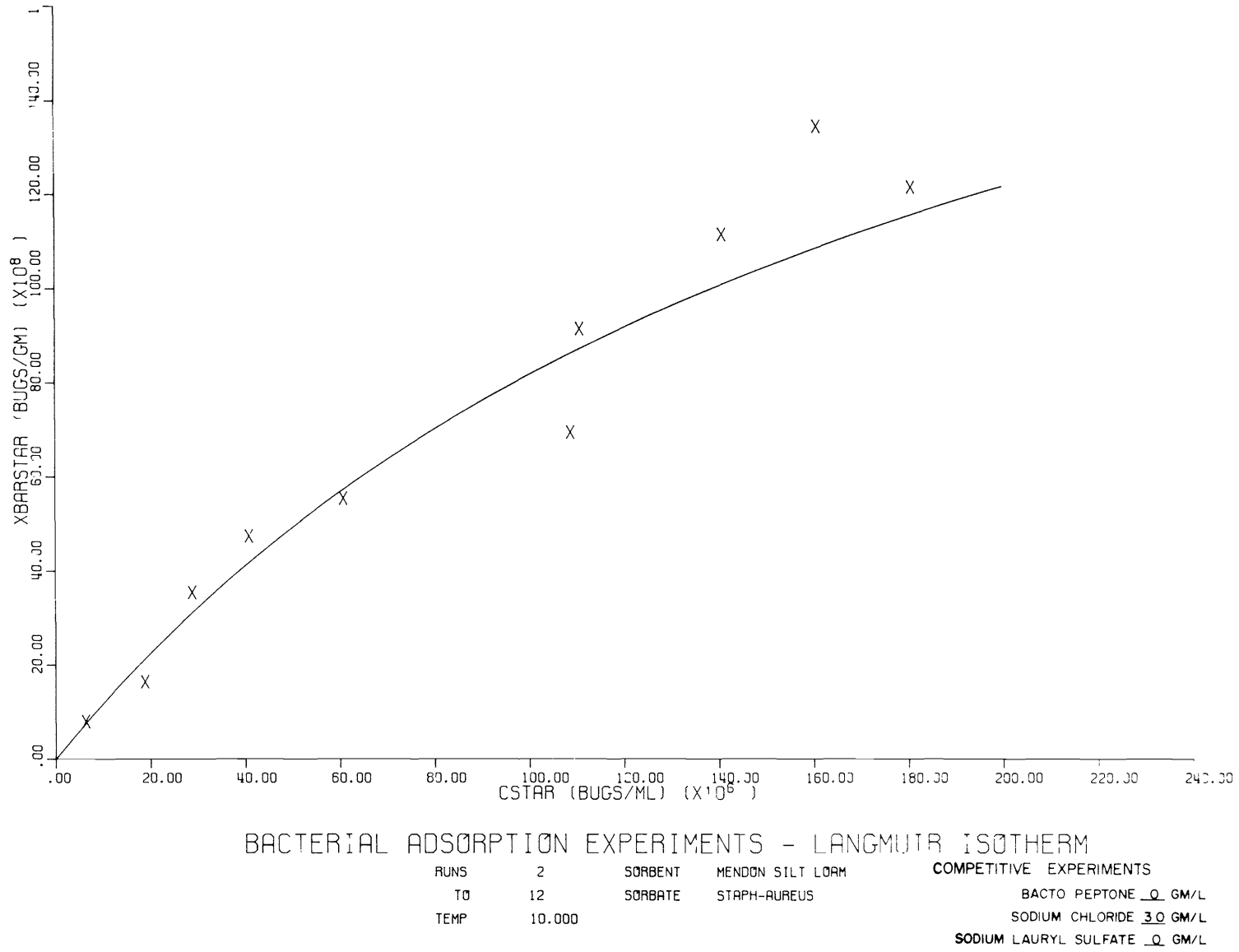


Figure G-2. Langmuir isotherm, runs 2-12, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 10C.

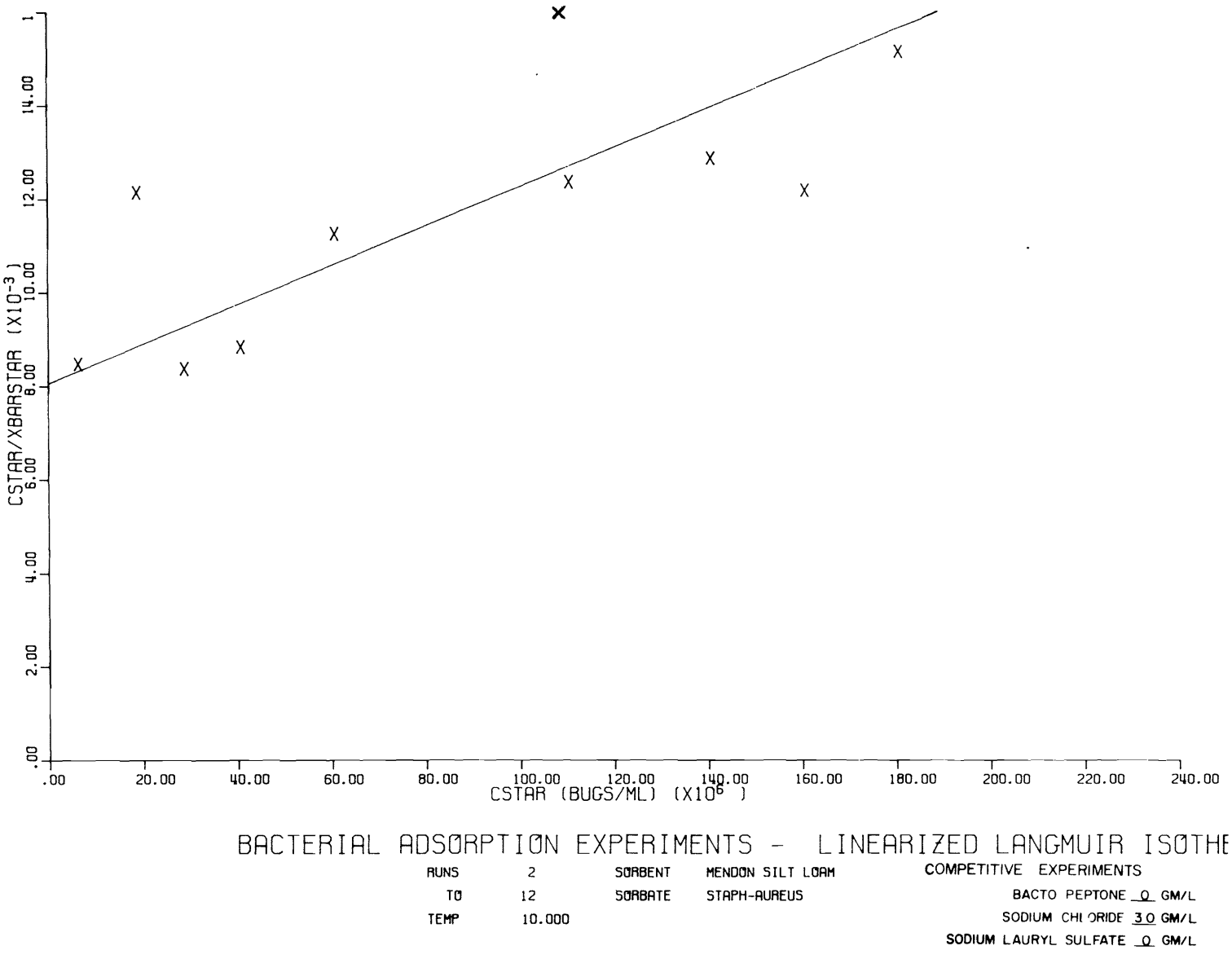


Figure G-3. Linearized Langmuir isotherm, runs 2-12, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 10C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 02/16/70
RUNS 1 TO 14

SORBATE STAPH-AUREUS
EDA-209
SORBENT MENDON SILT LOAM
3PCTNACL
TEMP 20.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .992
RSQ = .983
YINTERCEPT = 1/(ALPHA*XMAX) = .180048-02
SLOPE OF BEST FIT = .109975-09
ALPHA = .610812-07
XMAX = .909294+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
1	02/16/70	.70000+08	.90000+10	.87500-02
2	02/16/70	.50000+08	.60000+10	.83333-02
3	02/16/70	.30000+08	.50000+10	.60000-02
4	02/16/70	.13800+08	.40800+10	.34506-02
7	02/18/70	.20000+09	.80000+10	.25000-01
8	02/18/70	.18000+09	.90000+10	.20000-01
9	02/18/70	.13000+09	.90000+10	.14444-01
11	02/20/70	.15000+09	.80000+10	.18750-01
12	02/20/70	.12000+09	.80000+10	.15000-01
13	02/20/70	.11500+09	.70000+10	.16429-01
14	02/20/70	.80000+08	.90000+10	.88889-02

Figure G-4. Analysis of equilibrium data, runs 1-14, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 20C.

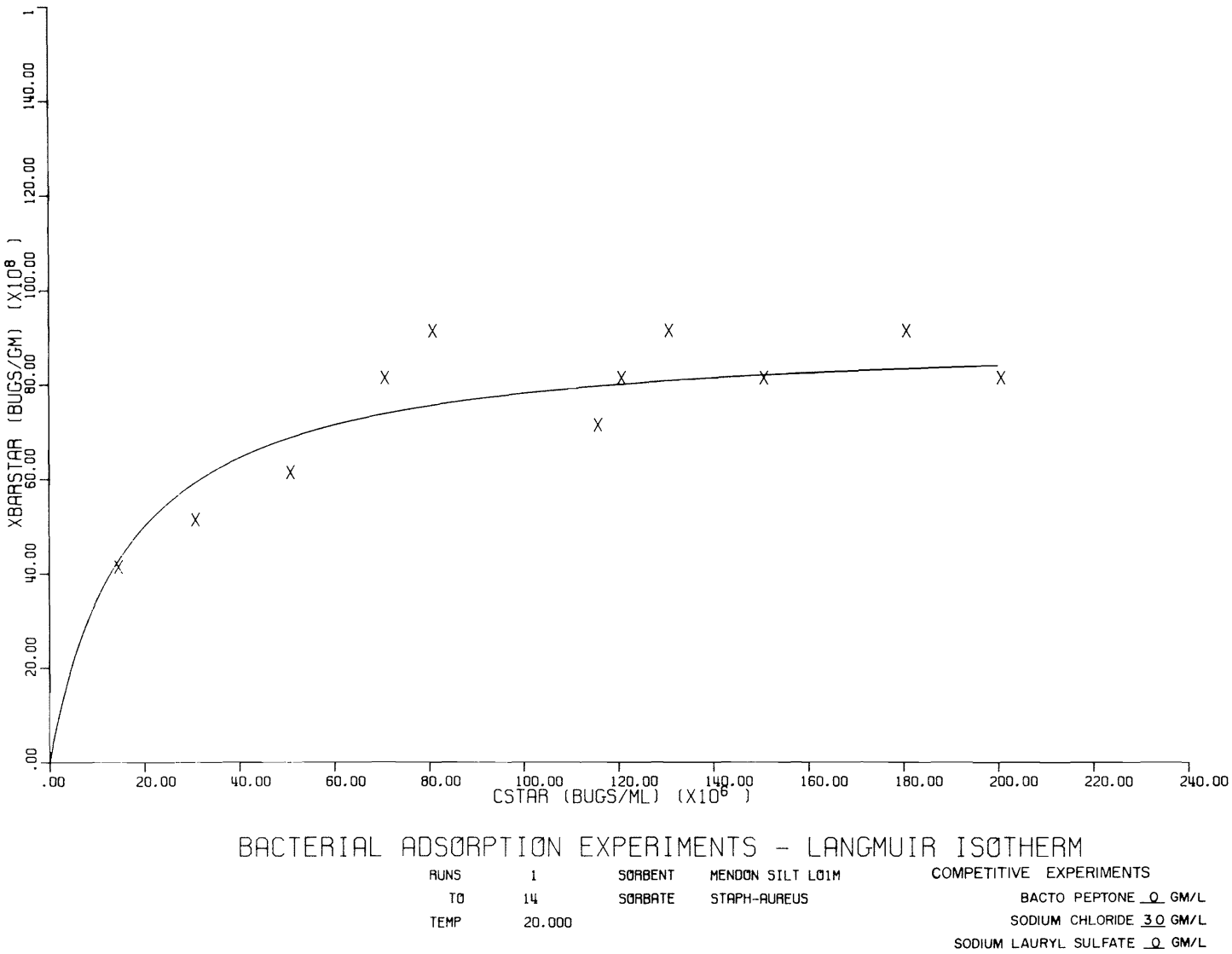


Figure G-5. Langmuir isotherm, runs 1-14, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 20C.

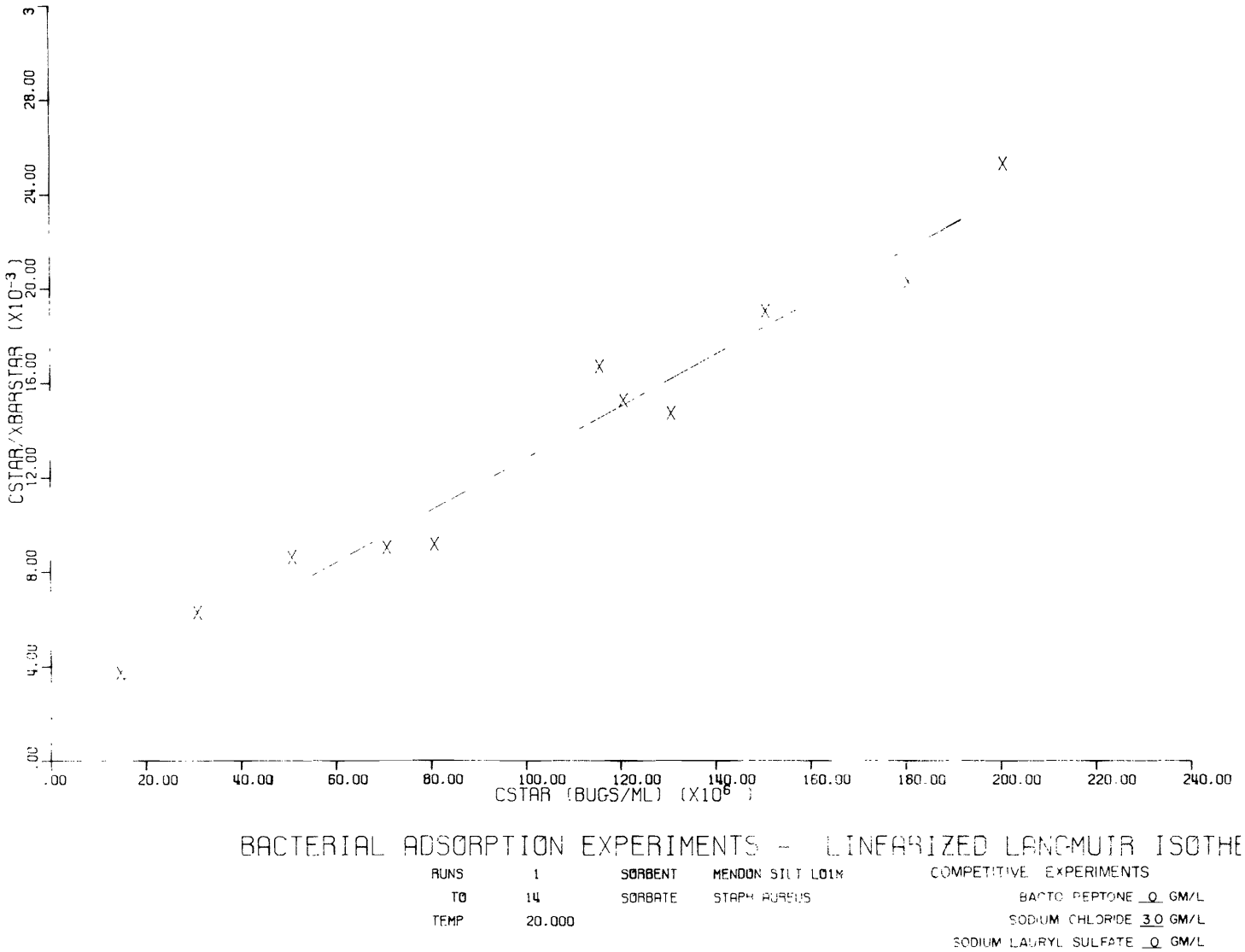


Figure G-6. Linearized Langmuir isotherm, runs 1-14, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 20C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 10/25/69
RUNS 3 TO 11

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM 3 PCT NACL
TEMP 27.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .919
R**2 = .844
Y INTERCEPT = 1/(ALPHA*XMAX) = .360565-02
SLOPE OF BEST FIT = .139447-09
ALPHA = .775653-07
XMAX = .773295+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

	RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
	3	10/25/69	.12000+09	.57000+10	.21053-01
	4	10/25/69	.30000+09	.68000+10	.13235-01
	5	10/25/69	.50000+08	.63000+10	.79365-02
	8	10/29/69	.92000+08	.60000+10	.15333-01
	9	10/29/69	.68000+08	.54000+10	.12593-01
	10	10/29/69	.20000+08	.44000+10	.45455-02
	11	10/29/69	.16000+08	.13000+10	.12308-01
Δ	1	10/25/69	.26700+09	.42000+10	.63571-01
Δ	2	10/25/69	.14800+09	.80000+10	.18500-01
Δ	7	10/29/69	.21500+09	.92000+10	.23370-01

Δ Off the scale, therefore not shown in Figures

Figure G-7. Analysis of equilibrium data, runs 3-11, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 27C.

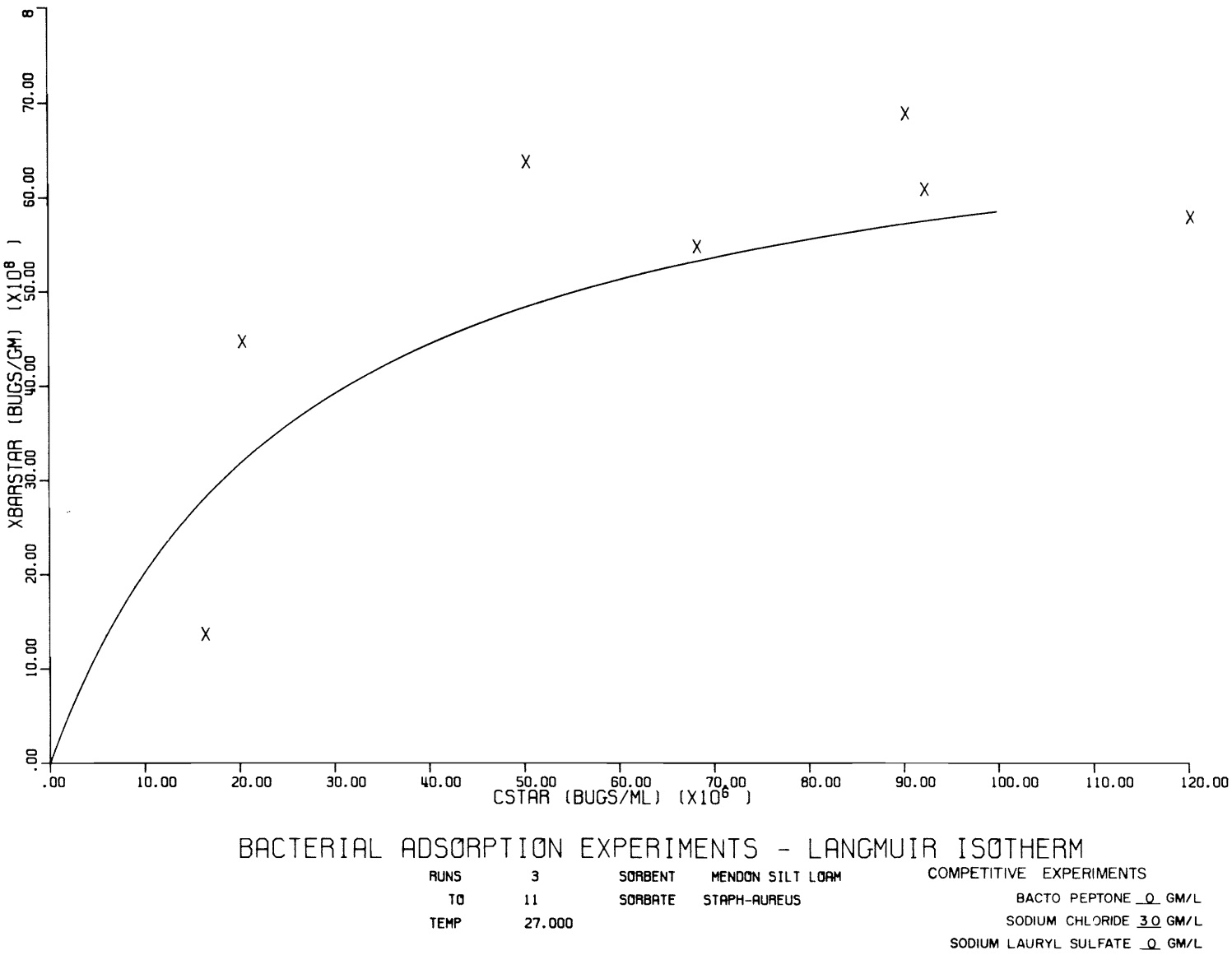


Figure G-8. Langmuir isotherm, runs 3-11, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 27C.

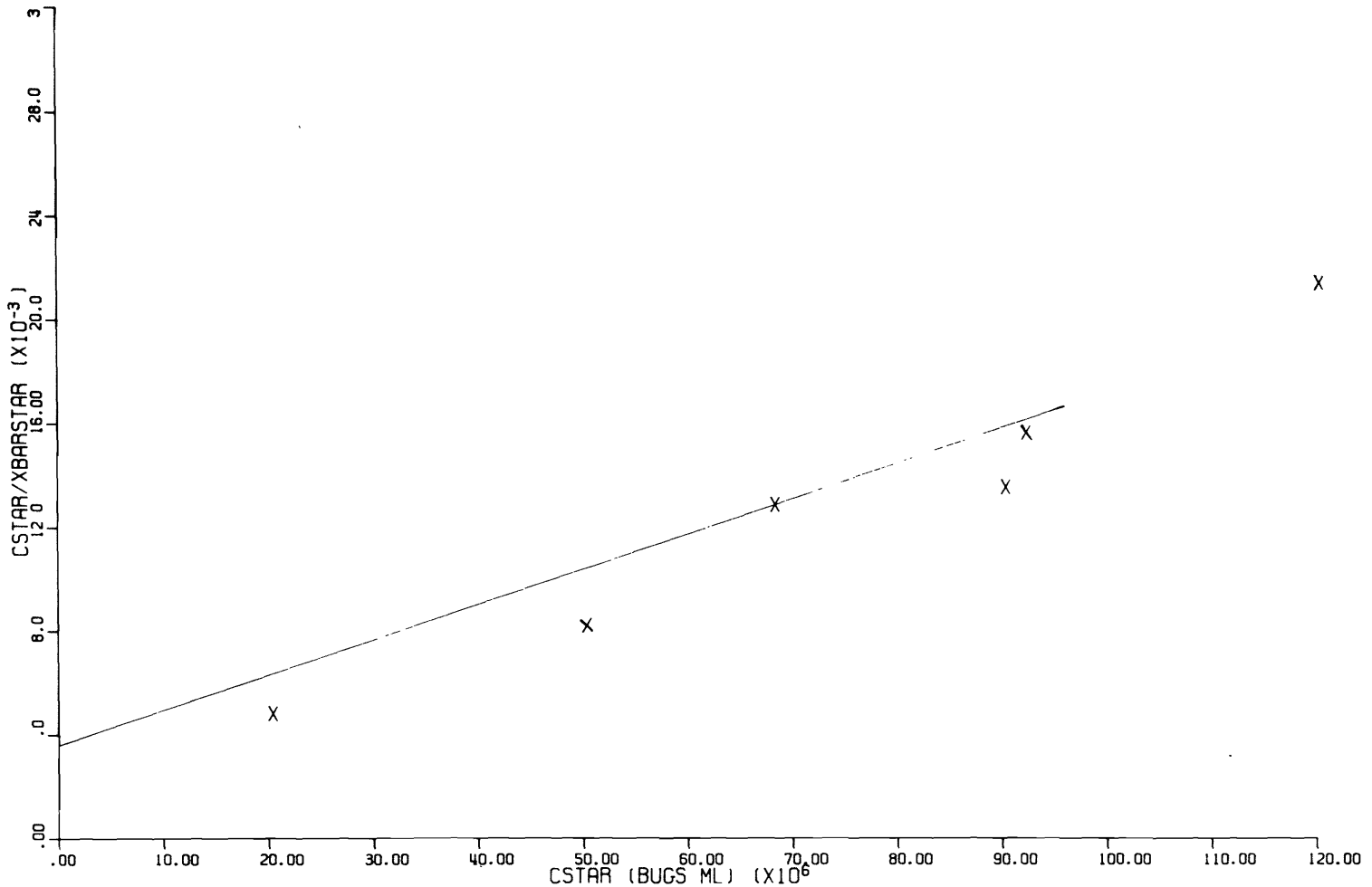


Figure G-9. Linearized Langmuir isotherm, runs 3-11, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 27C.

DETERMINATION OF ALPHA AND XMAX BY REGRESSION ANALYSIS OF LINEARIZED LANGMUIR ISOTHERM

DATE OF RUN 1 = 03/02/70
RUNS 2 TO 14

SORBATE STAPH-AUREUS FDA-209
SORBENT MENDON SILT LOAM 3PCTNCAL
TEMP 37.0 DEG. CENT.

REGRESSION ANALYSIS OF LINEARIZED ISOTHERM - RESULTS

R = .979
RSQ = .959
YINTERCEPT = 1/(ALPHA*XMAX) = .134613-02
SLOPE OF BEST FIT = .106088-09
ALPHA = .788098-07
XMAX = .942614+10

BASED UPON EQUILIBRIUM DATA FROM INDIVIDUAL RUNS

RUNS	DATE EXP BEGUN	C*	XBAR*	C*/XBAR*
2	03/02/70	.60000+08	.90000+10	.66667-02
3	03/02/70	.40000+08	.70000+10	.57143-02
4	03/02/70	.20000+08	.50000+10	.40000-02
5	03/02/70	.10000+08	.40000+10	.25000-02
7	03/05/70	.20000+09	.90000+10	.22222-01
8	03/05/70	.16000+09	.10000+11	.16000-01
9	03/05/70	.12500+09	.80000+10	.15625-01
10	03/05/70	.14500+09	.80000+10	.18125-01
12	03/10/70	.11000+09	.90000+10	.12222-01
13	03/10/70	.10000+09	.70000+10	.14286-01
14	03/10/70	.70000+08	.90000+10	.77778-02

Figure G-10. Analysis of equilibrium data, runs 2-14, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 37C.

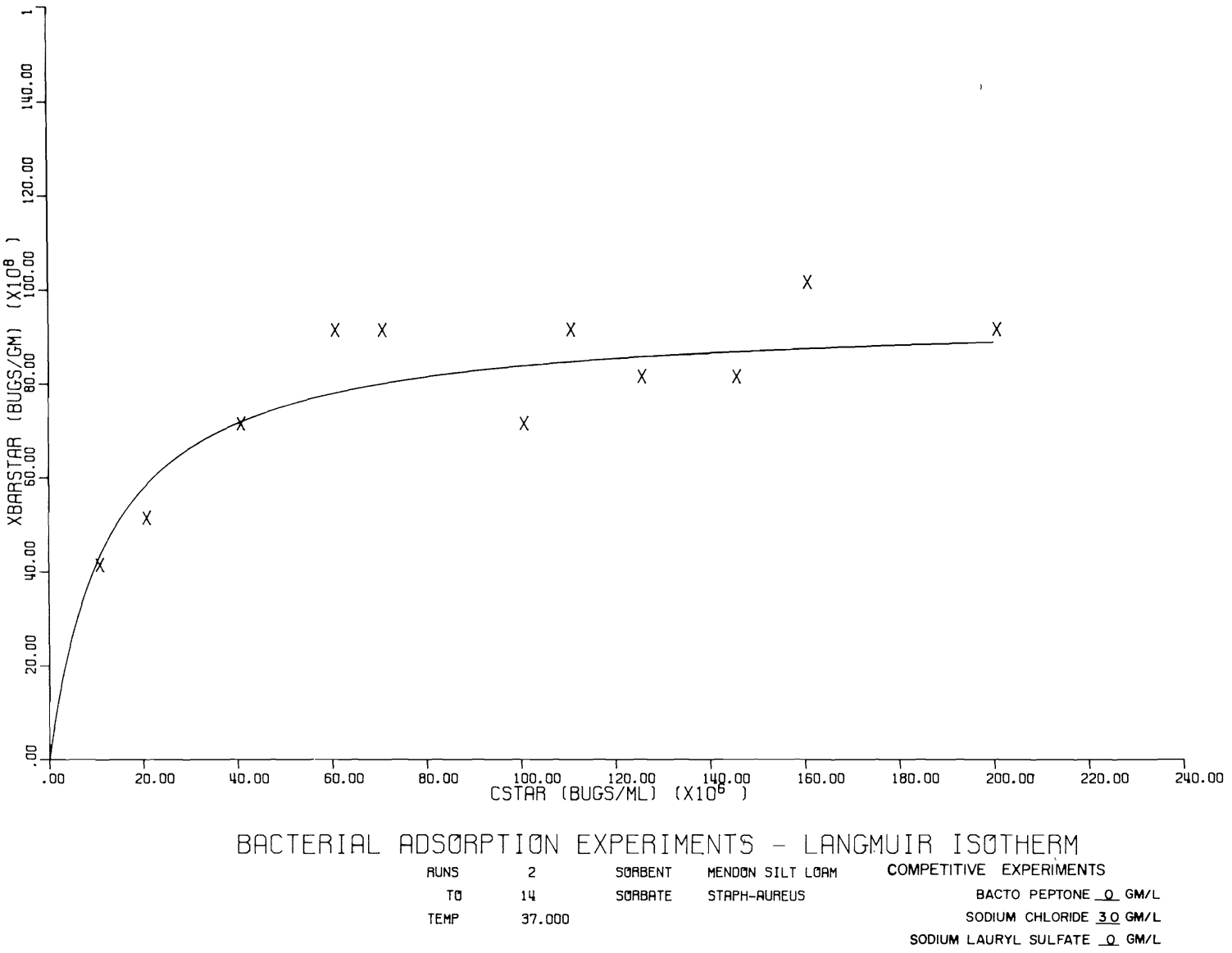


Figure G-11. Langmuir isotherm, runs 2-14, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 37C.

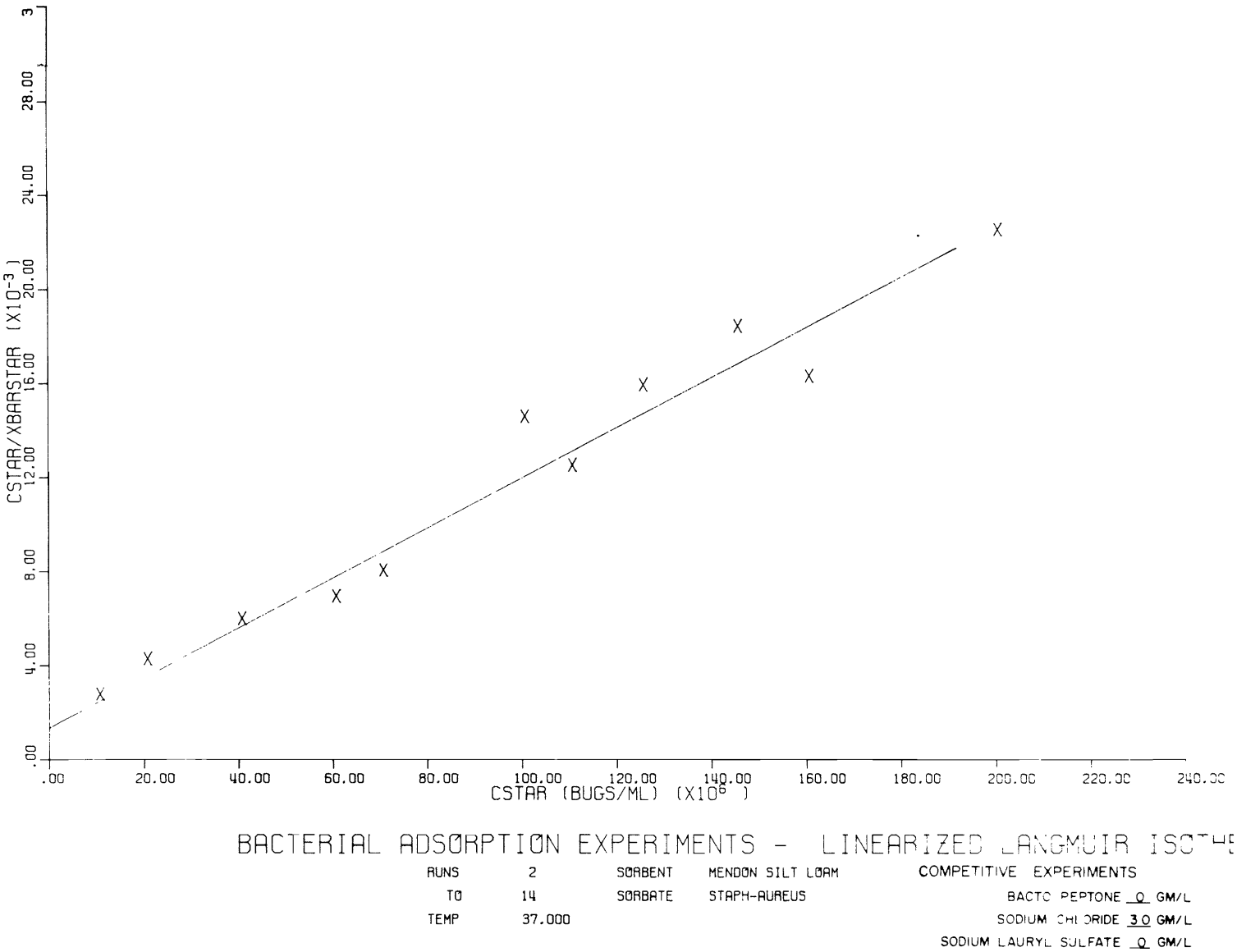


Figure G-12. Linearized Langmuir isotherm, runs 2-14, *S. aureus* and Mendon silt loam and 3.0 gm/l NaCl, 37C.

APPENDIX H

SOIL ANALYSIS—MENDON SILT LOAM[1]

UTAH STATE UNIVERSITY · LOGAN, UTAH 84321
AGRICULTURAL EXPERIMENT STATION
COOPERATIVE EXTENSION SERVICE

SOILS LABORATORY

February 11, 1970

D. R. Khairnar
Utah Water Research Laboratory
Campus

Soil Sample

Lab. No.	CEC(me/100g)	EC_e(mmhos)	(Exchangeable-me/100g) Na	K	Ca	Mg	OM(%)	pH
U70-31	26.7	1.0	.24	.61	40.0	9.0	4.4	7.4

Mechanical Analysis (hydrometer) →	Sand 2-.05 %	Silt .05-.002 %	Clay .005 %	Texture
	21	57	22	Silt Loam

[1] Sample obtained after air drying and sieving a sample of Mendon silt loam; the samples used in experiments, and reported above, are for the selected portion removed by sieve of .991 mm size.

APPENDIX I

BPROF PROGRAM LISTING AND OUTPUT

```
C      BACTERIAL ADSORPTION COLUMN PROFILES -USING TRANSPORT KINETICS
       DIMENSION  Z(500),C(500),XBAR(500),XSTR(500),DXDT(500),SBATE(3),
      2SBENT(3)
       REAL LAMBDA
       READ(5,100) LAMBDA,P,Q,A,  RHO,ALPHA,XMAX,CO,TDEL,ZDEL,TMAX,ZMAX,
      2IPRINT,INCR,SBENT,SBATE
  100 FORMAT(F15.5/F15.5/F15.5/F15.5/F15.5/E15.5/E15.5/F15.5/F15.5/F15.5
      2/F15.5/F15.5/110/110/3A6/3A6)
       AIMAX = ZMAX/ZDEL
       IMAX = AIMAX
       E = 2.718
       VSUM = 0.
       TIME = 0.
       KPRNT = 0
       ZZ = -ZDEL/2.
       K = 1
       V = Q/(A*P)
       PRHO = P*V*LAMBDA/(RHO*(1-P))
       DO 10 I = 1,IMAX
       ZZ = ZZ + 0.5
       XSTR(I) = 0.
   10  Z(I) = ZZ
       WRITE(6,200) Q,P,SBENT,CO,LAMBDA,SBATE,A,RHO,ALPHA,ZMAX,XMAX,ZDEL,
      2TDEL
  200 FORMAT       (1H1/52X'COLUMN PROFILES'/49X'CONVECTION KINETICS'///
      2,10X'COLUMN OPERATING CONDITIONS',12X'POROUS MEDIA PROPERTIES',23X
      3'SORPTION PROPERTIES'//13X'FLOW RATE, Q =',F5.1,1X'ML/MIN',26X'POR
      40SITY, P =',F5.2,14X'SORBENT',3A6/12X'FEED CONC, CO =',E9.4,1X'BUG
      5S/ML',7X'COLL. PROP. COEF., LAMBDA =',F6.2,1X'1/CM',8X'SORBATE',3A
      60/18X'AREA, A =',F5.2,32X'DENSITY, RHO =',F5.2,1X'GM/CC',8X'ALPHA
      7 =',E9.4,1X'ML/CELL'/16X'LENGTH, L =',F5.1,67X'XMAX =',E9.4,1X'CEL
      8LS/GM'//10X'ITERATION INCREMENTS'/
      910X'DELTAZ =',F5.2,1X'CM'/19X'DELTAT =',F5.2,1X'MIN'///)
       WRITE(6,300)
  300 FORMAT      (14X'TIME',5X'VOLUME',6X'DISTANCE',4X'CONCENTRATION',10
      2X'XBAR',10X'XSTAR',10X'DXDT'/14X'(MIN)',5X'(L)',10X'(CM)',8X'(BUGS
      3/ML)',9X'(BUGS/GM)',6X'(BUGS/GM)',6X'(BUGS/GM/MIN)'//)
C      WE BIG THE CALCULATION FOR CASES OF ZERO ADSORPTION
   55 CONTINUE
       IF(XMAX .GT. 0.)GO TO 55
       DO 35 I = 1,IMAX
       C(I) = CO
       DXDT(I) = 0.
   35  XBAR(I) = 0.
       GO TO 45
   55 CONTINUE
       DO 20 I = K,IMAX
       C(I) = CO/(E**(LAMBDA*(Z(I)-Z(K))))
       DXDT(I) = PRHO*C(I)
       XBAR(I) = XBAR(I) + DXDT(I)*TDEL
       XSTR(I) = ALPHA*C(I)*XMAX/(1.+ALPHA*C(I))
   20  IF((XSTR(I)-XBAR(I)) .LT. 0.) K = I
   45  TIME = TIME + TDEL
       VSUM = VSUM + Q*TDEL
       KPRNT = KPRNT + 1
       IF(KPRNT .LT. IPRINT)GO TO 65
       KPRNT = 0
       VOL = VSUM/1000.
       WRITE(6,400)TIME,VOL
  400 FORMAT(1H ,13X,F6.1 ,F10.2)
       WRITE(6,500)(Z(I),C(I),XBAR(I),XSTR(I),DXDT(I),I=1,IMAX,INCR)
  500 FORMAT(1H ,24X,F6.2,6X,E12.4,5X,E12.4,7X,E12.4,4X,E12.4)
       IF(TIME .LT. TMAX)GO TO 65
       END
```

Figure I-1. Column experiment program BPROF-listing.

COLUMN PROFILES
CONVECTION KINETICS

COLUMN OPERATING CONDITIONS

FLOW RATE, Q = 15.0 ML/MIN
FEED CONC, CO = .7000+03 BUGS/ML
AREA, A = 4.15
LENGTH, L = 10.0

ITERATION INCREMENTS
DELTAZ = .50 CM
DELTAT = 1.00 MIN

POROUS MEDIA PROPERTIES

POROSITY, P = .35
COLL. PROP. COEF., LAMBDA = .35 1/CM
DENSITY, RHO = 2.67 GM/CC

SORPTION PROPERTIES

SORBENT SILICA SAND
SORBATE STAPH. AUREUS
ALPHA = .0000 ML/CELL
XMAX = .0000 CELLS/GM

TIME (MIN)	VOLUME (L)	DISTANCE (CM)	CONCENTRATION (BUGS/ML)	XBAR (BUGS/GM)	XSTAR (BUGS/GM)	DXDT (BUGS/GM/MIN)
15.	.150					
		.25	.7000+03	.0000	.0000	.0000
		1.25	.7000+03	.0000	.0000	.0000
		2.25	.7000+03	.0000	.0000	.0000
		3.25	.7000+03	.0000	.0000	.0000
		4.25	.7000+03	.0000	.0000	.0000
		5.25	.7000+03	.0000	.0000	.0000
		6.25	.7000+03	.0000	.0000	.0000
		7.25	.7000+03	.0000	.0000	.0000
		8.25	.7000+03	.0000	.0000	.0000
		9.25	.7000+03	.0000	.0000	.0000
23.	.345					
		.25	.7000+03	.0000	.0000	.0000
		1.25	.7000+03	.0000	.0000	.0000
		2.25	.7000+03	.0000	.0000	.0000
		3.25	.7000+03	.0000	.0000	.0000
		4.25	.7000+03	.0000	.0000	.0000
		5.25	.7000+03	.0000	.0000	.0000
		6.25	.7000+03	.0000	.0000	.0000
		7.25	.7000+03	.0000	.0000	.0000
		8.25	.7000+03	.0000	.0000	.0000
		9.25	.7000+03	.0000	.0000	.0000
30.	.450					
		.25	.7000+03	.0000	.0000	.0000
		1.25	.7000+03	.0000	.0000	.0000
		2.25	.7000+03	.0000	.0000	.0000
		3.25	.7000+03	.0000	.0000	.0000
		4.25	.7000+03	.0000	.0000	.0000
		5.25	.7000+03	.0000	.0000	.0000
		6.25	.7000+03	.0000	.0000	.0000
		7.25	.7000+03	.0000	.0000	.0000
		8.25	.7000+03	.0000	.0000	.0000
		9.25	.7000+03	.0000	.0000	.0000

Figure I-2. BPROF output for simulation of bacterial breakthrough using a silica sand column.

COLUMN PROFILES
CONVECTION KINETICS

COLUMN OPERATING CONDITIONS

FLOW RATE, Q = 15.0 ML/MIN
FEED CONC. CO = .1000+08 BUGS/ML
AREA, A = 4.15
LENGTH, L = 10.0

POROUS MEDIA PROPERTIES

POROSITY, P = .32
COLL. PROP. COEF., LAMBDA = .36 1/CM
DENSITY, RHO = 1.55 GM/CC

SORPTION PROPERTIES

SORBENT MAT. CARB. B40C
SORBATE STRN. AUREUS
ALPHA = .1E43-05 ML/CELL
XMAX = .4838+10 CELLS/GM

ITERATION INCREMENTS

DELTAZ = .50 CM
DELTAT = 1.00 MIN

TIME (MIN)	VOLUM (L)	DISTANCE (CM)	CONCENTRATION (BUGS/ML)	XBAR (BUGS/GM)	XSTAR (BUGS/CM)	DXDT (BUGS/CM/MIN)
1.	.15					
		.25	.1000+08	.1208+05	.5219+07	.1208+04
		1.25	.7831+07	.8448+04	.3671+07	.8494+03
		2.25	.4943+07	.5972+04	.2582+07	.5972+03
		3.25	.3476+07	.4199+04	.1815+07	.4199+03
		4.25	.2444+07	.2952+04	.1276+07	.2952+03
		5.25	.1719+07	.2076+04	.8976+06	.2076+03
		6.25	.1208+07	.1459+04	.6311+06	.1459+03
		7.25	.8494+06	.1026+04	.4437+06	.1026+03
		8.25	.5972+06	.7215+03	.3120+06	.7215+02
		9.25	.4199+06	.5073+03	.2194+06	.5073+02
2.	.30					
		.25	.1000+08	.2415+05	.5219+07	.1208+04
		1.25	.7831+07	.1699+05	.3671+07	.8494+03
		2.25	.4943+07	.1194+05	.2582+07	.5972+03
		3.25	.3476+07	.8398+04	.1815+07	.4199+03
		4.25	.2444+07	.5905+04	.1276+07	.2952+03
		5.25	.1719+07	.4152+04	.8976+06	.2076+03
		6.25	.1208+07	.2919+04	.6311+06	.1459+03
		7.25	.8494+06	.2052+04	.4437+06	.1026+03
		8.25	.5972+06	.1443+04	.3120+06	.7215+02
		9.25	.4199+06	.1015+04	.2194+06	.5073+02
		↕	↕	↕	↕	↕
9.	1[illegible]					
		.25	.1000+08	.8457+[illegible]	.5219+07	.1208+04
		1.25	.7831+07	.5948+[illegible]	.3671+07	.8494+03
		2.25	.4943+07	.4191+[illegible]	.2582+07	.5972+03
		3.25	.3476+07	.2939+[illegible]	.1815+07	.4199+03
		4.25	.2444+07	.2067+[illegible]	.1276+07	.2952+03
		5.25	.1719+07	.1453+[illegible]	.8976+06	.2076+03
		6.25	.1208+07	.1022+[illegible]	.6311+06	.1459+03
		7.25	.8494+06	.7187+[illegible]	.4437+06	.1026+03
		8.25	.5972+06	.5050+[illegible]	.3120+06	.7215+02
		9.25	.4199+06	.3551+[illegible]	.2194+06	.5073+02

Figure I-3. BPROF output for simulation of bacterial breakthrough using an activated charcoal column.