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SAND82-0742 • Unlimited Release • UC-66c

Printed May 1982

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Thermal Conductivity of Aqueous Foam

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

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THERMAL CONDUCTIVITIES OF AQUEOUS FOAM

W. D. Drotning,** A. Ortega,* and P. E. Havey**

SAND--82-0742

DE82 016409

Abstract

Thermal conductivity plays an important part in the response of aqueous foams used as geothermal drilling fluids. The thermal conductivity of these foams was measured at ambient conditions using the thermal conductivity probe technique. Foam densities studied were from 0.03 to 0.2 g/cm³, corresponding to liquid volume fractions of the same magnitude. Microscopy of the foams indicated bubble sizes in the range 50 to 300 μ m for nitrogen foams, and 30 to 150 μ m for helium foams. Bubble shapes were observed to be polyhedral at low foam densities and spherical at the higher densities. The measured conductivity values ranged from 0.05 to 0.12 W/m-K for the foams studied. The predicted behavior in foam conductivity caused by a change in the conductivity of the discontinuous gas phase was observed using nitrogen or helium gas in the foams. Analysis of the probe response data required an interpretation using the full integral solution to the heat conduction equation, since the thermal capacity of the foam was small relative to the thermal mass of the probe. The measurements of the thermal conductivity of the foams were influenced by experimental effects such as the probe input power, foam drainage, and the orientation of the probe and test cell. For nitrogen foams, the thermal conductivity vs liquid volume fraction was observed to fall between predictions based on the parallel ordering and Russell models for thermal conduction in heterogeneous materials.

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I. INTRODUCTION

In analyzing the effects of heat transfer on temperatures of circulating aqueous foam during drilling in geothermal formations [1], it was concluded that the predominant variables which affect the magnitude of the temperatures are foam flow rate, foam effective thermal conductivity, and convective heat transfer phenomena such as flow regime and boundary layer separation at tool joints. It was noted that a fundamental lack of knowledge exists in the areas of foam rheology, convective heat transfer in foam-like fluids, and thermal property characterization. With the goal of increasing understanding of aqueous foam behavior in wellbores, and providing a data base for development of a numerical simulation capability, studies were conducted in each of these areas.

The purpose of this report is to document the experimental technique and the measured effective thermal conductivity of aqueous foams at ambient conditions. To the author's knowledge no data on the thermal conductivity of aqueous foams are available although the electrical conductivity of foams with bubble sizes on the order of 0.1 cm has been measured [2]. A number of existing theoretical models are presented for the thermal conductivity of heterogeneous materials including emulsions and foams and the appropriateness of using these models for predicting the thermal conductivity of aqueous foams is discussed. The analytical basis of the thermal conductivity probe technique is reviewed, with particular emphasis on anticipated probe thermal response for low thermal mass materials, like foams. The critical Rayleigh number for initiation of natural convection in aqueous systems is examined. The foam generation, thermal conductivity measurements and data analysis techniques are described in detail. Finally the conductivity results and physical description of the foam characterized by microscopy and drainage are presented.

II. BACKGROUND

A. Foam Structure

The structure and physical properties of an aqueous foam are closely related to the amount of liquid present and the texture. The former is given by the liquid volume fraction ϕ , defined by

$$\phi = \frac{\text{liquid volume}}{\text{foam volume}} \quad (1)$$

The texture is best quantified by the bubble size distribution since it is difficult to produce a monodisperse foam, i.e., one with uniform bubble size. In the range $0.02 < \phi < 0.10$ which is of greatest interest for drilling, it is more realistic to describe the foam as a structure composed of thin liquid films rather than as an agglomeration of packed spherical bubbles in a continuous liquid phase. Above a liquid volume fraction of 0.9 the latter description is appropriate and the dispersion is more truly a gaseous emulsion than a foam. The range inbetween is denoted a "gray" area by Bikerman [3].

An ideal foam bubble assumes a shape represented by a polyhedron (pentagonal dodecahedron) with polygonal faces (lamellae). The edges where the lamellae meet are referred to as Plateau borders. Although aqueous foams are stable in the gravitational field from the standpoint that bubble ascension by virtue of relative buoyancy is suppressed, they have measurable lifetimes since the liquid present in the lamellae and Plateau borders will continuously drain due to gravitation and capillary pressure gradients. When lamellae get thin enough they eventually burst, and the adjacent bubbles coalesce into one.

B. Thermal Conductivity of Foam

Many correlations have been reported in the literature to predict the thermal conductivity of heterogeneous materials in terms of the thermal conductivities of the components, the volume fractions of the components and their geometrical distribution [4]. The thermal conductivity of a material is defined as

the ratio of the macroscopic heat flux density to the macroscopic temperature gradient in the steady state. Thus the general definition does not distinguish between liquid mixtures such as foams, emulsions and suspensions and solid "mixtures" such as powders, unconsolidated sand and porous geologic media as long as the predominant heat transfer mechanism is molecular conduction. The expressions that have been derived in the literature for heterogeneous materials are either rigorous mathematical solutions for simple geometrical packing of elements or simple integrations of Fourier's conduction law through the assumed geometrical configuration with either linear isotherms or linear flux paths. Although the simplified geometries yield mathematically tractable differential equations and closed form expressions for effective conductivity k_{eff} , they represent highly idealized models of heterogeneous materials. Nonetheless, it has been demonstrated by Gorrington and Churchill [5], for example, that for the purpose of describing the macroscopic effective conductivity parameter k_{eff} , this approach yields excellent results in correlating data for a wide range of microscopically dissimilar materials. In Table 1, some of the more general relationships for k_{eff} are presented. The simple parallel and series ordered solutions serve as useful bounds. The other solutions are either for ordered cubes or spheres.

With respect to the prediction of the effective thermal conductivity of a two-component aqueous foam it is important to note that the model of foam as a structure composed of closely-packed polyhedra is in itself an idealization. It has already been noted that it is difficult to create a monodisperse foam, thus none is truly structurally homogeneous. Furthermore an aqueous foam, whether in a stagnant standing column or in a dynamic flowing situation, is never rigid, as for example a plastic urethane foam of the same density, but is characterized by liquid drainage and a constant rearrangement of cells seeking a more stable configuration. Hence the transport property which we refer to as apparent thermal conductivity is by its very nature not a pure property as

Table 1. Generalized Equations for Effective Thermal Conductivity for Various Geometric Arrangements

i. parallel ordered
$$\frac{k_{eff}}{k_C} = (1 - v_d) + v_d \frac{k_d}{k_C} \quad (2)$$

ii. series ordered
$$\frac{k_{eff}}{k_C} = \frac{1}{(1 - v_d) + v_d \frac{k_C}{k_d}} \quad (3)$$

iii. Russell [6]: cubes in a cubic array; linear isotherms
$$\frac{k_{eff}}{k_C} = \frac{1 - v_d^{2/3} + \frac{k_d}{k_C} v_d^{2/3}}{1 - v_d^{2/3} + v_d + \frac{k_d}{k_C} (v_d^{2/3} - v_d)} \quad (4)$$

iv. son Frey [7]: cubes in a cubic array; linear heat flow
$$\frac{k_{eff}}{k_C} = \frac{1 - v_d^{1/3} + v_d + \frac{k_C}{k_d} (v_d^{1/3} - v_d)}{1 - v_d^{1/3} + \frac{k_C}{k_d} v_d^{1/3}} \quad (5)$$

v. Rayleigh [8], Devries [9]: regular array of uniform spheres in contact.
 simple cubic array, $a = 1.31$
 body - centered cubic, $a = .129$
 face - centered cubic, $a = .0752$

$$\frac{k_{eff}}{k_C} = 1 - \frac{3v_d}{\left(\frac{2 + k_d/k_C}{1 - k_d/k_C}\right) + v_d - \left(\frac{1 - k_d/k_C}{4/3 + k_d/k_C}\right) (a) v_d^{10/3} + \dots} \quad (6)$$

vi. Maxwell [10]: random distribution of spheres; no contact
$$\frac{k_{eff}}{k_C} = \frac{\frac{k_d}{k_C} + 2 - 2v_d \left(1 - \frac{k_d}{k_C}\right)}{\frac{k_d}{k_C} + 2 + v_d \left(1 - \frac{k_d}{k_C}\right)} \quad (7)$$

vii. Bruggeman [11]:
infinite range of bubble sizes
in continuous phase.

$$1 - V_d = \frac{\frac{k_{eff}}{k_C} - \frac{k_d}{k_C}}{\left(\frac{k_{eff}}{k_C}\right)^{1/3} \left(1 - \frac{k_d}{k_C}\right)} \quad (8)$$

k_d = thermal conductivity of discontinuous phase (gas)
 k_C = thermal conductivity of continuous phase (liquid)
 V_d = volume fraction of discontinuous phase = $1 - \phi$

for single component materials, but more nearly an effective transport property which correlates the quasi-steady transfer of heat through the foam by the combined action of conduction through the continuous phase, conduction through the discontinuous phase, convective circulation within bubbles, and convective transport by liquid flowing in the veins and borders. Because of the coupled nature of these distinct phenomena it is difficult to describe analytically the relative contributions of each. We can however experimentally measure the transfer of heat in a foam as though it were a static medium, and then deduce the augmentation of heat transfer by means other than conduction by comparison with accepted conduction models as given in Table 1. The usefulness and applicability of such property data will depend on its sensitivity to the measurement technique used and on the temperature and heat transfer rate at which measurements are made.

Because of the non-conductive transfer mechanisms described above, general equations such as those given in Table 1 can serve only as a basis for predicting limiting lower bounds on the effective thermal conductivity of foams. Furthermore the effect of the different geometric models and packing which distinguishes these analytical equations would seem secondary compared to nonconduction contributions. It is important nonetheless to examine these equations for their utility as limiting cases in lieu of deriving new simplified expressions for complex mechanisms.

For the case where liquid drainage and bubble coalescence and rearrangement are neglected, it would appear that the irregular bubble structure of foams should share characteristics of both an array of closely packed spheres, as in the Rayleigh [8] model, and an array of ordered cubes as in the Russell [6] and son Frey [7] models. In the range $0.1 < \phi < 0.9$, the bubble structure approaches a spherical geometry as the liquid volume increases, in which case the Rayleigh

model of an array of face centered cubic packed spheres should yield a theoretically sound asymptote for the case of a monodisperse foam. Objections have been raised by various investigators regarding the use of models which do not account for size distribution of the dispersed bubbles. Accordingly, the Bruggeman [11] model, which applies to the situation in which both phases are topologically equivalent, is often used in representing the conductivity of emulsions. More recently Meredith and Tobias [12] developed a model which treats the dispersion as consisting of particles of only two different sizes. Using k_d for the discontinuous (gas) phase and k_c for the continuous (liquid) phase conductivities, they found good agreement with data on emulsions where $\frac{k_d}{k_c} > 0.1$, but poor agreement with electrical conductivity data on foam [13] where k_d/k_c was assumed to be zero. All of their data and the data for foams as well were found to lie between equations 7 and 8.

Several investigators have measured the electrical conductivity of foams and have generally found that the data are bounded by the equations of Maxwell [10] and Bruggeman [11]. Recently, Chang and Lemlich [2] have extended the approach of Meredith and Tobias [12] to allow any bubble size distribution. They found that their data compared well with the data of Clark [13]. The relationship between k_{eff}/k_c and V_d was unique and could be predicted fairly well with increasingly detailed bubble size distribution functions in their model. It is noteworthy that in these investigations of the electrical conductivity of foam, the conductivity of the gas phase has been assumed to be zero. The effort has thus been to develop a model which more nearly describes the effects of bubble size distribution on the effective path length for electrical conduction through the foam. In this sense the work of Chang and Lemlich [2] should require no further refinement.

It should now be apparent that because of its obvious similarity to electrical conductivity as an intensive property of the foam, the effective foam thermal conductivity should, for negligible drainage and coalescence affects, be uniquely

related to the foam bulk density (represented by the volume fraction of the liquid phase) and the thermal conductivity of the gas and liquid components. Unlike the electrical conductivity, the gas thermal conductivity cannot be neglected even though the ratio of gas to liquid conductivities k_d/k_c is small, on the order of 0.04 for nitrogen foam. In Figure 1 the simplified relationships presented in Table 1 are shown for a gas-to-liquid conductivity ratio of 0.0437 (nitrogen to water at standard conditions). Except for the Rayleigh model, it is seen that as the liquid volume fraction goes to zero, all of the models predict the conductivity of the discontinuous phase. The Rayleigh model does not reach the correct value in the limit because only one term of the infinite series is retained. It is seen that the models given by Eqs. 4 through 7 give approximately the same effective conductivity in the range of interest. Eq. 8 predicts a conductivity which diverges from the other results with increasing liquid volume fraction. The results of references 2 and 12 would be found to lie between the Maxwell and Bruggeman equations as has been noted.

A few additional comments should be made regarding the differences between effective electrical and thermal conductivity of aqueous foams. Success in measuring the electrical conductivity of foams has been due largely to the fact that the measurement is noninterfering, that is the passage of electrical current through a bulk foam does not alter its structure significantly during the measurement period. This is not true for any finite heat transfer through the foam bulk, hence the measurement of a thermal conductivity by conventional means is more difficult. The general equations which have been found to predict electrical conductivity in foams strictly speaking also may be used to predict thermal conductivity only in the limit of negligible heat transfer (or more properly, negligible temperature gradients) in the foam. With this in mind, the present measurements of the thermal conductivity will serve to demonstrate the appropriateness of using this limit for practical calculations of the thermal conductivity.

Figure 1. Effective thermal conductivity vs liquid volume fraction for models described in text.

C. Thermal Conductivity Measurement Technique

For a pure liquid, the measurement of the effective thermal conductivity must be performed under experimental conditions which do not induce natural convection in the fluid. Generally, such conditions are achieved by minimizing any thermal gradient established to generate heat flow and thereby determine the fluid conductivity. For the aqueous foams of interest here, these considerations apply, with the additional constraint that the measurement must be performed in a time scale during which liquid drainage from the sample does not significantly affect the result. To minimize the measurement time, the transient line source technique was chosen, as implemented by the thermal conductivity probe [4, 14].

The analytical solution for the response of an infinite medium to a line source was presented by Carslaw and Jaeger [15]. The solution gives the temperature rise in the medium at any time following application of a constant heat input to an infinitely long, thin, massless wire ("line"). A thermal conductivity probe consists of a long, thin heater element and a temperature sensor, usually located on-axis at the center of the heater length. Several treatments of the analytical solution employing the probe have been given; the report by Koski [14] discusses several of interest to this work. Generally, the analytical solutions for the probe include the effects of thermal mass of the probe, thermal contact resistance of the probe-medium interface, and the finite dimensions (length and radius) of the probe. Various analytical solutions may be used to describe the early time region, the long time region, or the entire time period of the probe thermal response. (The latter is an integral, nonalgebraic solution.)

It can be shown [14, 15] that after a time period during which probe thermal capacity and contact resistance effects are important, the temperature rise of the probe may be described by

$$k = \frac{q}{4\pi(T_2 - T_1)} \ln \left(\frac{t_2}{t_1} \right) \quad (9)$$

where k is the thermal conductivity of the material, q is the input heat flux, and T_1 is the temperature at time t_1 . Where the approximation described by Eq. (9) is adequate, a plot of the probe temperature rise vs the log of time will yield a straight line, the slope of which determines the thermal conductivity k . This is the so-called straight line method for analysis of thermal conductivity probe data. Other data analysis techniques have been employed, including a nonlinear least squares fit to the data using the full integral solution [14]. For the current work, the straight line analysis method was used; however, the full integral solution was used 1) to predict qualitatively the shape of the probe response (temperature vs time) for the low thermal mass material of interest here, 2) to examine the effects of probe diameter on the expected thermal response, and 3) to identify the correct linear region of the data for subsequent analysis.

Two of the important parameters which influence the theoretical response of a thermal conductivity probe are the contact resistance h between the sample and the probe, and ω , the thermal capacity ratio, which is twice the ratio of ρC_p of the material to ρC_p of the probe. It has been shown that nonzero values of h can significantly delay the entry into the straight line region of the probe response curve (dimensionless temperature rise vs $\ln \tau$, where τ is the Fourier modulus, or the dimensionless time parameter), even to the point of presenting an early (but false) straight line region. (See, for example, the work by Koski [14].) Values of ω between 0 and 1 can cause similar behavior, which is of particular interest in this study.

Using the procedures given by Koski, the probe response was computed for various values of ω with $h = 0$, and is shown in Fig. 2. For the foams of

Figure 2. Theoretical thermal conductivity probe response using the full integral solution (described in text). Various values of ω are shown, where $\omega = 2\rho C_p(\text{material})/\rho C_p(\text{probe})$ ($h = 0$, no contact resistance).

interest, a contact resistance parameter $h = 0$ is indicated. For the 0.020" diam. probe used in these experiments, ρC_p was calculated to be approximately 2.2×10^6 J/m³-K, while for the foam material, $\rho C_p \sim \rho_{\text{foam}} \times 4.2$ J/g-K. Thus, for a foam with $\rho_{\text{foam}} \sim 0.1$ g/cm³, we have $\omega \sim 0.4$, and the predicted probe response indicates the nonlinear solution asymptotes the straight line region from below, following an inflection point region which can easily be mistaken for the straight line region (see Fig. 2). The theoretical response curves can also be used to predict the dependence on the probe radius. Since $\tau \sim \text{time}/(\text{radius})^2$, a larger diameter (b_2) probe requires a longer real time t (by a factor of b_2^2/b_1^2) to achieve the true straight line region than does a smaller probe (diameter b_1). Variation of probe diameter can be used in an experiment, then, to verify the predicted probe response and select the true straight line region.

D. Natural Convection Effects

A true measurement of the conductivity of a fluid medium should be devoid of any contributions to the overall heat transfer by natural convection. At this juncture it would be useful to distinguish between large scale natural convection and local circulation of fluid within individual bubbles. The presence of a heated surface in the bulk foam fluid will induce a density gradient between the fluid immediately surrounding the probe and the undisturbed fluid and the resulting instability will produce bulk fluid deformation by virtue of buoyant forces overcoming the viscous forces in the thermal boundary layer. It will be shown that the bulk foam viscosity is sufficiently high such that large scale convection can be made negligibly small compared to conduction in a practical time domain. On the scale of individual gas bubbles in the bulk, the presence of any finite gradient in the temperature across the bubble structure will induce local circulation of the gaseous phase within, and therefore the transfer of heat will not be restricted to pure molecular conduction.

Practically speaking, the effective thermal conductivity measured would thus be perturbed by local circulation. At this point it is assumed that this contribution will be of the same order as the large scale convection below a critical Rayleigh number and will be neglected.

The influence of natural convection on the probe heat transfer will increase with time as the probe temperature increases. The calculation of the thermal conductivity from the transient conduction model thus is restricted to times below the critical convection limit. In the transient radial problem, the definition of a critical Rayleigh number is not truly applicable since both the temperature elevation, ΔT , and the length scale, L , determined by the thermal front are transient. However, if one assumes that the transient temperature field in the medium surrounding the probe can be represented by an instantaneous pseudo-steady condition as suggested by Van der Held and Van Drunen [16], the instantaneous temperature elevation and the effective penetration radius can be used to define a pseudo-steady-state Rayleigh number.

In steady state, the temperature difference ΔT across a cylindrical annulus is given by [15]

$$\Delta T = \frac{Q}{2\pi k} \ln \left(\frac{b}{a} \right) \quad (10)$$

where

k = thermal conductivity of the material in the annular gap

a = radius of inner cylinder

b = radius of outer cylinder

Q = heat transfer rate per unit length of cylinder from hotter cylinder to cooler.

For the transient line source case, we assume the long time solution with no contact resistance, given by [14]

$$\frac{k\Delta T}{Q} = \frac{1}{4\pi} \left[\ln \left(\frac{4\tau}{C} \right) + \frac{1}{2\tau} + \left(\frac{\omega - 2}{2\omega\tau} \right) \ln \left(\frac{4\tau}{C} \right) + \dots \right] \quad (11)$$

where

$$C = 1.7811$$

$$\tau = \text{Fourier modulus, } \frac{\alpha t}{a^2}$$

$$\alpha = \text{thermal diffusivity, } \frac{k}{\rho C_p}$$

$$a = \text{probe radius}$$

$$t = \text{time}$$

$$\omega = \text{thermal capacity ratio, } \frac{2(\rho C_p)_{\text{mat}}}{(\rho C_p)_{\text{probe}}}$$

$$k = \text{effective thermal conductivity}$$

$$\rho = \text{density}$$

$$C_p = \text{heat capacity.}$$

In Eq. (11), ΔT is defined as $T(a, t) - T_\infty$. From Eq. (10), the steady-state solution, we solve for the radius b in terms of a and ΔT , and then substitute for ΔT from Eq. (11), thereby assuming that the temperature at $r = b$ is undisturbed in the transient case. Thus,

$$b = a \exp \left[\frac{2\pi k \Delta T}{Q} \right] \quad (12)$$

$$= a \cdot \exp \left[\frac{1}{2} \left[\ln \left(\frac{4\tau}{C} \right) + \frac{1}{2\tau} + \left(\frac{\omega - 2}{2\omega\tau} \right) \ln \left(\frac{4\tau}{C} \right) \right] \right] \quad (13)$$

and the effective length scale to be used in the Rayleigh number is

$$L = (b - a) \quad (14)$$

The Rayleigh number may be expressed as

$$Ra = \frac{\rho^2 C_p g \beta \Delta T L^3}{\mu k}, \quad (15)$$

where β is the thermal expansion coefficient and μ is the dynamic foam viscosity.

It can be shown that for a two component foam the effective expansivity is given by the mass weighting of the component expansivities:

$$\beta_{\text{eff}} = \frac{\phi \rho_l \beta_l + (1 - \phi) \rho_g \beta_g}{\phi \rho_l + (1 - \phi) \rho_g} \quad (16)$$

where the subscripts g and l represent gas and liquid respectively. The coefficients for air and water at standard conditions have been taken as $0.34 \times 10^{-2} \text{ K}^{-1}$ and $0.18 \times 10^{-3} \text{ K}^{-1}$, where $\rho_g = 1.1 \text{ Kg/m}^3$ and $\rho_l = 1000 \text{ Kg/m}^3$. As an example, we choose $\phi = 0.1$ and the following corresponding material parameters:

$$k = 0.067 \text{ W/m-K (Maxwell model, Eq. (7))}$$

$$C_p = 4.1 \times 10^3 \text{ J/Kg-K (mass weighting of the components, as in Eq. (16))}$$

$$\rho = 100 \text{ Kg/m}^3$$

$$\mu = 0.049 \text{ Kg/m-s (Bingham viscosity, as measured by Beyer, et al. [17])}$$

$$\beta = 0.21 \times 10^{-3} \text{ K}^{-1} \text{ (from Eq. (16)).}$$

For this example, we assume the following experimental parameters:

$$\omega = 0.4$$

$$a = 0.25 \text{ mm (0.010" probe radius)}$$

$$Q = 0.25 \text{ W/m (typical heater power)}$$

For a given foam (ϕ) and Q, Eq. (15) can be solved, yielding Ra as a function

of time and therefore temperature rise ΔT . It is well known that natural

convection effects are negligible in a heated horizontal annulus when $Ra < 1000$.

For the above example, this occurs at $\tau = 4301$, or $t = 1645 \text{ s}$, for which $\Delta T =$

2.72 K , $\ln \tau = 8.4$ and $L = 24.3 \text{ mm}$. The onset of natural convection is thus seen

to limit the experimental measurement time and the temperature rise for a given

input power. Based on the results of an earlier section, it would appear that the time limitation of $\ln \tau = 8.4$ is not severe, and that the probe response will be sufficiently developed to allow meaningful analysis by the straight line method. A more severe limitation to measurement time is likely to be liquid drainage from the foam, which essentially results in a time-varying liquid volume fraction ϕ .

III. EXPERIMENTAL DETAILS

In this section, we will describe the foam generator, the probe and its auxiliary equipment, and the measurement procedure used to acquire and reduce the data.

A. Foam Generator

A laboratory scale foam generating system was built in order to generate and flow aqueous foam directly into a test cell containing the thermal conductivity probe. A schematic of the system is shown in Fig. 3. The packed tube foam generator (static mixer) consisted of a 3/8 inch I.D., 8 inch long stainless steel tube packed with coarse brass wool. The surfactant mixture consisted of 3 w/o MSA type V foam concentrate in water. This surfactant system was selected because it produces a highly stable foam at liquid volume fractions between 0.02 and 0.2. The reservoir containing the surfactant mixture was pressurized to 50 psig with the gas used to generate the foam (either helium or nitrogen). The foam was generated by flowing the pressurized surfactant mix and the gas through the generator tube. The density of the foam was adjusted by controlling the gas and liquid flow rates by means of metering valves. After generation, the foam was directed into the test cell (glass cylinder, 12 in. long x 2 in. I.D.) where the thermal conductivity measurement was made.

To generate a foam, the following procedure was used. The surfactant mixture was loaded into the reservoir and the reservoir and gas line were pressurized to 50 psig. Values V_8 and V_{10} were opened and valve V_9 was closed to initially direct

Figure 3. Foam generator schematic diagram.

the foam flow to the drain. Valves V_6 and V_7 were opened and then V_4 and V_5 (metering valves) were alternately adjusted until the desired combination of surfactant mixture and gas flow was attained. The flow ratio of the surfactant mixture and gas determined the density of the foam given a particular static mixer and gas species. Flow rates for these measurements were typically between 20 and 50 ml/min for the MSA type V concentrate and either nitrogen or helium gas.

Foam flowed out the drain until all large air bubbles were expended. Then the flow was directed through the test cell by opening valve V_9 and closing valve V_8 . After the test cell had been filled with foam and the conductivity probe temperature had come to equilibrium with the foam, the foam was sampled at the test cell outlet to determine the foam density. The density measurement was made by weighing a known volume of the foam. Foam densities used in making these measurements were between 0.02 and 0.2 g/cm³. Valves V_6 and V_7 were closed to stop the foam flow. The cell pressure was monitored (meter M_1) until the pressure was less than 1 psig. At this time V_9 and V_{10} were closed. The probe temperature was again monitored and when it had stabilized to better than $\pm 0.1^\circ\text{C}$, a run was begun.

B. Thermal Conductivity Probe System

The thermal conductivity probe used for these measurements is shown schematically in Fig. 4. The probe sheath is an 0.020 inch O.D., 0.002 inch wall, 8 inch long stainless steel tube. Internally there is a 0.012 inch O.D. bifilarly wound heater coil made from 0.001 inch diam. Constantan wire. Inside the heater coil and centered on the probe length is a 0.0005 inch by 0.005 inch Chromel "P" thermocouple. The heater and thermocouple are encapsulated in Hysol #6020 with actuator B. Some of the heater wire extends into the plastic terminal where external leads are brought out of the probe. The length of heater in the terminal does not contribute to heating the probe. Therefore, the actual power density (Q) is only 98.2% of the apparent power density calculated using the applied

Figure 4. CSI thermal conductivity probe schematic diagram.

current and voltage. The probe was purchased from Custom Scientific Instruments, Whippany, NJ; we will refer to the device as the CSI probe.

The data acquisition and control system is shown in Fig. 5. Power for the probe was provided by a regulated, adjustable dc power supply. The output of the power supply may be applied to either a dummy resistor load or the conductivity probe by means of a latching relay under computer control. The dummy resistor had the same heater resistance as the particular probe being used. This resistive load was used to stabilize the power supply before power was applied to the probe heater. The voltage and current to the dummy resistor and probe were measured with digital multimeters. The probe temperature was measured with a digital voltmeter which read the output of an electronic ice point connected to the probe thermocouple.

A Hewlett-Packard System 1000 minicomputer was used to control the thermal conductivity measurements. The computer enabled the latching relay, acquired and stored the data (probe temperature vs time), and was used for data reduction and analysis.

C. Data Acquisition and Analysis Procedure

When the sample to be measured was at thermal equilibrium, a computer program called PROBE was run. The computer measured the initial probe thermocouple output; power was then applied to the probe and temperature versus time data were recorded. The current and voltage to the probe were recorded at the beginning of a run and were monitored during the course of the run by the operator. The current and voltage were used to determine the power density applied to the probe. For the results reported here, power densities between 0.05 and 0.5 W/m were used. When program PROBE terminated, either by a preset time limit or by operator control, power was removed from the probe. The raw data were then reduced using a computer program THCON.

DATA ACQUISITION AND CONTROL SYSTEM

Figure 5. Data acquisition and control system schematic diagram.

The computer program THCON is an interactive graphics program for analysis of thermal conductivity probe data. The program is written in FORTRAN and is implemented on a Hewlett-Packard System 1000 minicomputer with an HP2647A Graphics Terminal. The program includes a command processor with a self-help feature to guide the user through the available commands.

A typical session using THCON utilizes the following functions. The user enters the name of the file which contains the data to be analyzed (ordered pairs of temperature in degrees C vs time in seconds). The program then requests the probe parameters describing the particular run being analyzed (voltage, current, length, and power factor). The time data are then shifted to a time scale relative to application of probe power, and then converted to $\ln(\text{time})$. The temperature vs $\ln(\text{time})$ data are then plotted on the graphics terminal. The user then selects the digitize mode. A graphics cursor appears on the terminal screen, and the user moves the cursor to identify and bound a region of the data for the straight-line analysis. In the calculate mode, the program fits a least squares straight line to the data in the selected region, graphically illustrates the linear fit, computes the thermal conductivity, and outputs the results, including the rms deviation of the fit. The user may then select a different linear region in an attempt to find a better linear fit. Once the user is satisfied with the fit, the results may be listed on a computer line printer and/or plotted on a graphics plotter. An example of the latter output is shown in Fig. 6. The vertical dotted lines indicate the bounds selected for the linear analysis, and the dashed line represents the least squares linear fit. The program fully utilizes the numerical processing capability of the computer while allowing the user to visually select various regions of the data for analysis.

FOAM..091GM/ML.CSI1 IN VESSEL

$k = .085 \text{ W/m-K}$
 Probe Power = .242 W/m
 Std. Dev. = .008 C

Figure 6. Typical output from program THCON. Data is for N_2 foam, density = 0.091 g/cm^3 . Linear region chosen for analysis is between $\ln t = 3.3$ (27 s) and $\ln t = 5.4$ (221 s). Upward curvature past $\ln t = 6$ is probably due to drainage effects.

IV. RESULTS AND DISCUSSION

A. Foam Physical Description

A number of photographs were taken through a 7X microscope of foams generated on a horizontal glass plate. The foams were free-standing, many bubble layers thick, and open to the atmosphere. Both top and bottom illumination were used, but an attempt was made to minimize the heat flux to the foam from the illuminating lamps. The microscope was focused on the top layer of the foam for the photography. Although the pictures are of foams with a surface exposed to the atmosphere, we believe that the resultant pictures qualitatively represent the bulk foam. Quantitative measurements of bubble shapes, sizes and distributions, film thicknesses, drainage rates, etc., may be used to describe these foams by parameters other than the liquid volume fraction ϕ or the foam density ρ . (We will use ϕ and ρ interchangeably, as they differ by less than 1% for the materials studied here.) Besides the gas species, the surfactant mixture, and ϕ , the average bubble size likely depends on the details of the static mixer, as well.

Some typical foams are pictured in Fig. 7, which shows three different nitrogen foam densities at approximately the same time (2-3 min) following generation. As the foam density ρ decreases, the film (lamella) thickness decreases, as shown by the increased optical transmission of the bubbles and the decreased bubble separation. The bubble shape shows the expected trend from polyhedral at low density to spherical at the high density. Generally speaking, the bubble diameters for these foams range from 50 to 300 μm . There appears to be relatively more of the smaller bubble sizes (less than 100 μm) in the highest density foam. In any event, the bubble sizes and the size distributions are not dramatically different over this range of foam density.

The effects of foam drainage are displayed in Fig. 8, which shows a foam with $\rho = 0.125 \text{ g/cm}^3$ at 30 s, 10 min, and 30 min after generation of the foam.

Figure 7. Microscopy of N₂ foam bubbles, 2-3 minutes following foam generation, at various densities.

$t = 30 \text{ s}$

$t = 10 \text{ min}$

$t = 30 \text{ min}$

TIME AFTER FOAM GENERATION

—
200 μm

Figure 8. N_2 foam bubbles, density = 0.125 g/cm^3 , at various times following foam generation.

As time progresses, the foam drains by gravity, leaving an effectively lower density foam. The foam at 30 min is more transparent than earlier in time and shows some evidence of polyhedral bubbles relative to earlier times. Following foam generation, the bubble sizes are in the 50 to 300 μm range, but as time progresses (10 to 30 min), gaseous diffusion causes a coalescence of bubbles, leaving relatively few bubbles less than 200 μm diam., and some as large as 400 μm at 30 min.

The foams generated with helium gas had surprisingly different bubble sizes than the nitrogen foams. An example of a helium foam is shown in Fig. 9 ($\rho = 0.056 \text{ g/cm}^3$, 1 min after generation). Here, the bubbles range from 30 to 120 μm and appear to be spherically shaped.

B. Thermal Conductivity

Prior to analysis of the probe data by the straight-line method, it is important to identify correctly the true linear region. In a previous section, the material-to-probe thermal capacity ratio parameter ω was estimated to be 0.4 for the probe and materials of interest. An examination of the curves in Fig. 2 reveals that the predicted response was actually observed, as displayed in Fig. 6 -- that is, both prediction and measurement display an early "false" linear region, an inflection in the curve, and an approach to the true linear region from below. For the $\rho = 0.09 \text{ g/cm}^3$ foam in Fig. 6, $\alpha/a^2 \sim 2.5 \text{ s}^{-1}$, so that for an inflection near $(\ln t) \sim 3$ ($t \sim 30 \text{ s}$) in Fig. 6, we expect an inflection near $(\ln \tau) \sim 4$ in Fig. 2, which is generally consistent with the theory for $\omega = 0.4$.

Fig. 6 also demonstrates that the linear behavior is valid to $t \sim 300 \text{ s}$, beyond which the temperature- $\ln$ time response becomes nonlinear. This nonlinear behavior is likely due to foam drainage, since natural convection should not be significant until $t \sim 1600 \text{ s}$, at which time the radial extent of the temperature disturbance is $\sim 2.4 \text{ cm}$, approximately the size of the test cell.

—
200 μm

Figure 9. He foam bubbles, density = 0.056 g/cm^3 , ~1 min. after generation.

Thus test cell boundary effects should not be observed for times less than 1600 s, either.

As the foam drains, the density (and therefore the thermal conductivity) will decrease, which qualitatively explains the upward curvature of temperature vs $\ln$ time at the longest times (Fig. 6). This nonlinear response region, which we argue is correlated to foam drainage, was observed to occur at earlier times for 1) He as opposed to N_2 foams, and 2) horizontal as opposed to vertical orientation of the probe and test cell. In both cases, drainage occurred sooner than for a vertical probe orientation in nitrogen foam. First, He foams were observed to drain much faster than nitrogen foams. Secondly, in the vertical probe orientation, the temperature sensor was below some 10 cm of foam, but only 2.5 cm for the horizontal case. Thus, the effects of drainage would be observed sooner in the horizontal case.

For a relatively dense nitrogen foam ($\rho = 0.16 \text{ g/cm}^3$), 1 part in 15 (by volume) of the liquid in the foam drained to the bottom of a 10 cm tall column in approximately 2 min. This corresponds to a reduction of the bulk density of about 7% in this time period, which should not significantly affect the bulk foam properties. The bubble pictures support a similar drainage rate. For the $\rho = 0.125 \text{ g/cm}^3$ foam, there appears little difference between the foam at 30 s (Fig. 8) or at 2 min (Fig. 7). In summary, for a vertical probe (using the 0.020" diam. CSI probe) on nitrogen foams, data appear to be valid for times less than 200 to 300 s, considering the effects of drainage, bulk natural convection, test cell boundaries, and nonlinear regions of the probe thermal response.

A CSI probe of similar design but with a threefold increase in radius was also used for some measurements. Only by comparison with the theoretical response shown in Fig. 2 was it learned that these data were incorrectly analyzed using the "false" linear region. The second, "true" linear region was not observed

before drainage effects could be noted and the measurement was terminated. (For a 3X increase in probe diameter, the physical time must be increased by 9X to attain the same Fourier modulus.)

Some additional observations were made to examine the effects at the probe interface. A horizontal probe under several layers of foam bubbles was examined under the microscope. No unusual bubble size change was observed at the foam-probe boundary, and no significant fluid film thickness was observed on the probe. A power level of a ~ 0.6 W/m was applied to the probe (the maximum used in the measurements of k), and the observations under the microscope were continued for several minutes. No bubble movement, bursting, or size change was observed, either next to the probe or in the bulk.

The thermal conductivity of the liquids used in the foam generation were measured using the CSI probe as well. For the surfactant (concentrate), $k = 0.44$ W/m-K, while $k = 0.63$ W/m-K for water (compared to a handbook value of 0.61) and $k = 0.62$ for the 3 w/o mixture.

The results of the foam thermal conductivity measurements vs foam density are shown in Fig. 10 for nitrogen foams and in Fig. 11 for helium foams. All measurements were made at ambient conditions. These figures show all the data, including the various probe power levels Q and two probe orientations (vertical or horizontal). The data are given in tabular form in the Appendix. Also shown in the figures are the predicted curves assuming the parallel ordering model, which should yield the highest theoretical conductivity for a heterogeneous mixture. Generally, the data obey the trend of the parallel model prediction, though the scatter in the data is significant, and is certainly greater than the anticipated $\pm 10\%$ precision of the probe technique [4]. Some of the scatter is undoubtedly due to the inability to accurately control or characterize all of the parameters (e.g., viscosity, bubble size and distribution) which could cause

Figure 10. Thermal conductivity vs foam density for N_2 foam showing both vertical and horizontal probe orientations. Straight line is the parallel ordering model.

Figure 11. Thermal conductivity vs foam density for He foam. Straight line is the parallel model.

variation in k . In this study, the foam is characterized strictly by the surfactant mixture, the gas species, and the bulk foam density. Much of the scatter in the measured data is due to artifacts of the experiment, which we discuss next.

Foam conductivities were measured in both horizontal and vertical probe orientations. Fig. 10 shows the results for nitrogen foams with both orientations for $\rho \sim 0.1 \text{ g/cm}^3$. The horizontal configuration yields a higher (apparent) conductivity. This may be explained by effects of drainage on thermal transfer from the probe. In the vertical case, fluid drainage down the probe results in little temperature change of the probe, since the draining fluid is heated by the probe. In the horizontal configuration, however, the fluid on the heated probe is replaced by cooler fluid draining from above. Thus, the probe is cooled by drainage, with the result that the sample medium appears to have an erroneously high conductivity. The majority of the runs were made using the vertical configuration, as seen in Fig. 10.

Another experimental effect which was observed was the dependence of the measured conductivity on the input probe power Q . Generally, the higher the Q used (and therefore the higher ΔT generated), the higher the measured k . This dependence appeared to be stronger as the foam density decreased. Some representative results are shown in Table 2. (The figures show data for all values of Q .) Most of the data were obtained using $Q \sim 0.25 \text{ W/m}$ or less.

Table 2. Thermal Conductivity vs Probe Power Density.
Nitrogen foam, vertical probe orientation.

$\phi \sim 0.06$		$\phi \sim 0.12$		$\phi \sim 0.20$	
$Q(\text{W/m})$	$k(\text{W/m-K})$	$Q(\text{W/m})$	$k(\text{W/m-K})$	$Q(\text{W/m})$	$k(\text{W/m-K})$
0.067	0.056	0.067	0.089	0.101	0.118
0.242	0.070	0.204	0.097	0.243	0.126
0.661	0.095	0.490	0.106	0.660	0.138
0*	0.053	0	0.087	0	0.116

*linear extrapolation to $Q = 0$.

The effect of Q on measured k is not well understood in this instance. One can postulate effects such as gas convection within individual bubbles, or temperature dependent fluid surface tension in the film separating two bubbles. In any event, an increase in the value of measured k corresponds to the occurrence of an additional heat transfer mechanism, which, in these aqueous foams, is apparently enhanced by an increased heat flux at a heated boundary.

Frequently one varies Q in measurements on liquids in an attempt to observe convective effects, but one generally expects to find a threshold power Q (at the onset of convection) below which k ceases to vary with Q . The data shown in Table 2 show no such threshold effect. However, a linear extrapolation of k vs Q to $Q = 0$ (zero power) should provide a lower bound for k at any value of ϕ . The $Q = 0$ values are given in Table 2.

We conclude that measured values of k for horizontal configurations or high probe power levels are incorrectly high, and that the most representative data are for the vertical probe orientation with Q below some arbitrarily-defined limit. Fig. 12 shows the vertical probe data from Fig. 10, for $Q < 0.1$ W/m. The $Q = 0$ values in Table 2 are also plotted. From Fig. 12 it is apparent that the parallel ordering model indeed represents an upper bound to k vs ϕ for these foams, and that the most representative data lie below the parallel model, nearer to models which, like the Russell model, predict lower values of k at any foam density. (The Russell model was chosen only as a representative example; the scatter in the data preclude any choice of one model over another.)

For the helium foams in Fig. 11, the scatter is somewhat larger than in Fig. 10. The helium foams were difficult to measure, as the foams typically reduced in volume by ~20% in 5 min. or less (by downward fluid drainage and upward loss of gas). In any event, the data for He in Fig. 11 show a behavior with density qualitatively similar to that in Fig. 10 for nitrogen foams, and the variation in k with gas species is evident.

Figure 12. Nitrogen foam thermal conductivity vs density. Vertical probe orientation, and only values measured using probe power $Q < 0.1$ W/m. The $Q = 0$ values were obtained by linear extrapolation of the data in Table 2.

V. SUMMARY

The thermal conductivity of aqueous foam for drilling applications was measured at ambient conditions using the line source thermal conductivity probe technique. This report describes in detail the experimental apparatus and procedure for foam generation, data acquisition, and thermal conductivity data analysis. Several models of the thermal conductivity of heterogeneous media are presented from the literature.

In the following, we summarize a number of observations and conclusions from this study:

1. The effective thermal conductivity k of the foams vs liquid volume fraction ϕ generally obeyed the trend of the parallel ordering model, though the scatter in the data was significant. Conductivity values measured ranged from 0.05 to 0.12 W/m-K.
2. Measured values of k were larger in horizontal configurations as opposed to vertical, due to foam drainage.
3. Measured values of k decreased with decreasing probe input power Q . Values of k obtained by linear extrapolation to $Q = 0$ provide a lower bound on k for any foam density.
4. The most representative data were judged to be those obtained with vertical probe orientations for $Q < 0.1$ W/m. These data fall generally between the parallel ordering and Russell models.
5. Measured values of k for helium foams displayed a similar behavior with foam density, and the predicted variation of k with gas species was observed.
6. Analysis of natural convection in these foams predicted convective effects for times greater than 1600 s in a typical case.
7. The full integral solution for heat transfer from the probe was necessary to predict the shape of the observed thermal response of the probe; the shape was dominated by probe thermal capacity effects in the early time region.

8. For the 0.020" diam. probe, the linear temperature vs $\ln$ time region developed after $t \sim 20$ s.
9. For the 0.060" diam. probe, the linear region of the probe response did not develop prior to effects due to foam drainage.
10. Drainage effects on the probe response were observed for $t > 200$ s.
11. Microscopy of foam bubbles at ambient conditions displayed polyhedral bubble shapes for $\phi \sim 0.3$ and spherical shapes for $\phi \sim 0.12$ in nitrogen foams.
12. Bubble sizes ranged from 50 to 300 μm with nitrogen foams, and 30 to 120 μm in helium foams, shortly after generation of the foams.
13. Effects of fluid drainage from the foams were observed by microscopy. As time progressed, drainage caused decreased wall thickness, a change in the bubble size distribution (fewer small bubbles), a slight increase in bubble size, and changes in shape (from spherical to polyhedral).
14. Microscopy of a heated probe in foams showed no gross bubble movement, bursting, or size change over the time duration used in a measurement.

VI. ACKNOWLEDGEMENTS

The authors gratefully acknowledge P. Rand for the design, and P. C. Montoya for the construction of the foam generator, L. Mondy for assistance in the microscopic photography, and D. McVey and J. Koski for valuable discussions on the analytical aspects of thermal conductivity probe response.

VII. REFERENCES

1. Blackwell, B. F. and Ortega, A., "An Assessment of Heat Transfer to Aqueous Foam Fluids in Geothermal Drilling Applications," Sandia Internal Memorandum, RS 5512/80/1, August 1980.
2. Chang, K. and Lemlich, R., J. Colloidal and Interface Sci. 73, 224, 1980.
3. Bikerman, J. J., Foams, Springer-Verlag, NY, 1973.
4. Drotning, W. D., Koski, J. A. and Havey, P. E., "Development of a Technique for Measurement of the Thermal Conductivity of Powders at High Temperatures," SAND 81-0631,* NUREG/CR-2287, Sandia National Laboratories, Albuquerque, NM, August 1981.
5. Gorrington, R. L. and Churchill, S. W., "Thermal Conductivity of Heterogeneous Materials," Chem. Eng. Prog. (57 no. 7), July, 1961.
6. Russell, H. W., J. Am. Ceram. Soc. 18, 1, 1935.
7. von Frey, G. S., Z. Elektrochem. 38, 260, 1932.
8. Lord Rayleigh, Phil. Mag. 34, 481, 1892.
9. Devries, D. A., Bull. Intern. Inst. Refrig., Annexe 1952-1 32, 115, 1952.
10. Maxwell, J. C., A Treatise on Electricity and Magnetism, Oxford Univ., 3rd. Ed., Vol. 1, 1892, p. 440.
11. Bruggeman, D. A. G., Ann. Phys., 24, 636, 1935.
12. Meredith, R. E. and Tobias, C. W., J. Electrochemical Soc., 108, 286, 1961.
13. Clark, N. O., Trans. Faraday Soc., 44, 13, 1948.
14. Koski, J. A., "Analysis of Thermal Conductivity Probes for High Temperature Applications, SAND 81-0106,* Sandia National Laboratories, Albuquerque, NM, April 1981.
15. Carslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids, Oxford University Press, 1959.

16. Van der Held, E. F. M., and Van Drunen, F. G., Physica XV no. 10, Oct. 1949, pp. 865-881.
17. Beyer, A. H., et al., "Flow Behavior of Foam as a Well Circulating Fluid," SPE Paper No. 3986, October 1972.

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APPENDIX. Measured Thermal Conductivity k vs Foam Density ρ , Probe Power Q , Gas Species, and Probe Orientation.

A. N_2 foam, Vertical

<u>Run Designation</u>	<u>$Q(W/m)$</u>	<u>$\rho(g/cm^3)$</u>	<u>$k(W/m-K)$</u>
TNA 42B	.059	.028	.047
TNA 43	.102	.028	.054
TN 38	.067	.047	.057
TN 39B	.101	.047	.067
TNA 127	.207	.058	.079
TN 34	.067	.067	.056
TN 33B	.242	.071	.070
TN 35	.661	.071	.095
TN 08B	.452	.090	.091
TN 32B	.242	.091	.085
TN 06	.105	.096	.074
TN 07	.203	.096	.082
TN 10B	.066	.100	.081
TN 04	.203	.104	.101
TN 03	.105	.115	.097
TN 09	.066	.101	.082
TN 21	.067	.127	.089
TN 19	.204	.129	.097
TN 20B	.490	.128	.106
TN 23B	.102	.153	.093
TN 24	.242	.148	.106
TN 22	.657	.151	.112
TN 29	.101	.172	.113
TN 31	.242	.172	.120
TN 30	.660	.174	.129
TN 28B	.101	.198	.118
TN 27	.243	.192	.126
TN 25	.242	.190	.128
TN 26B	.660	.189	.138
TNA 47	.202	.107	.096

B. N₂ foam, Horizontal

<u>Run Designation</u>	<u>Q(W/m)</u>	<u>ρ(g/cm³)</u>	<u>k(W/m-K)</u>
TNA 44B	.203	.096	.125
TNA 45B	.203	.103	.125
TNA 46	.203	.105	.119
TNA 49	.660	.112	.126
TNA 48	.104	.109	.092

C. He foam, Vertical

TNA 74	.202	.034	.114
TNA 100	.192	.038	.152
TNA 101	.284	.038	.183
TNA 99	.099	.043	.112
TNA 80	.415	.048	.139
TNA 97	.419	.058	.221
TNA 98	.197	.061	.200
TNA 96	.199	.070	.182
TNA 79	.641	.076	.177
TNA 95B	.195	.084	.200
TNA 86B	.418	.088	.180
TNA 73	.202	.090	.173
TNA 77	.639	.096	.193
TNA 75	.195	.099	.183
TNA 76	.197	.122	.182
TNA 78	.640	.125	.216
TNA 103	.197	.165	.191
TNA 104	.125	.168	.166
TNA 84	.417	.176	.257
TNA 102	.447	.180	.231
TNA 85	.417	.188	.243

D. He foam, Horizontal

TNA 88	.418	.074	.207
TNA 87	.418	.090	.228

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