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THERMODYNAMICS OF IRREVERSIBLE PROCESSES

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TECHNICAL REPORT
ONRL-33-50

THERMODYNAMICS OF IRREVERSIBLE PROCESSES

Summary

An informal two day conference on the subject of "Thermodynamics of Irreversible Processes" was held on January 5 and 6, 1950, at the Butterwick Research Laboratories of Imperial Chemical Industries in Welwyn. About 25 people attended, including a few guests from The Netherlands. The intention was largely to acquaint the audience with recent developments and points of view in the field, rather than to bring together a group of specialists.

The lectures and discussions each day were introduced by Professor S.R. de Groot of the University of Utrecht; The Netherlands, who presented a review of both the theoretical and experimental aspects of the subject. Among the half dozen talks were discussions of theoretical and experimental aspects of thermal diffusion in liquids and gases, and thermo-osmosis in membranes, remarks on the theory of the steady state and a review of theoretical work in irreversible thermodynamics. Two interesting matters brought up at the meeting concerned a possible improvement in the separation of He^3 from He^4 with a thermal diffusion column and the optical technique for measurement of thermal diffusion in liquids applied by C.C. Tanner in 1927.

A list of participants is given in Appendix A.

22 March 1950

Approved by:
C.E. Sunderlin
Scientific Director

Prepared by:
Paul M. Marcus
Scientific Liaison Officer

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THERMODYNAMICS OF IRREVERSIBLE PROCESSES

Introduction:

The following six brief reports are summaries of papers and discussions at an informal conference sponsored by Imperial Chemical Industries (I.C.I.) on January 5 and 6, 1950, at their Butterwick Research Laboratories in Welwyn, about 25 miles from London. The arrangements were made by Mr. M.T. Sampson of I.C.I. with the assistance of Professor A. Michels of the University of Amsterdam and Professor S.R. de Groot of the University of Utrecht.

The general subject for discussion was the Thermodynamics of Irreversible Processes, alternatively referred to as Non-Equilibrium Thermodynamics. The purpose was to acquaint the audience, particularly members of the I.C.I. laboratories, with the general state of the work in this field, rather than bring together a group of specialists to review all the latest developments.

Professor de Groot gave a long introductory talk on the theoretical background of the subject leading up to and including the work of Onsager, which in 1931 set the subject on a sound basis. He also gave a long introductory talk on work on thermal diffusion both in gases and liquids. These phenomena require for their proper treatment new methods which extend the region of application of classical thermodynamics, and are of interest today because of the application of the thermal diffusion column to separation of isotopes.

Of particular interest was the lecture of Dr. C.C. Tanner of I.C.I., on thermal diffusion measurements in liquid mixtures performed 25 years ago by an optical method which measured concentration changes by refractive index changes. Dr. Tanner realized the importance of making the length of the diffusion column as small as practicable to reduce the time required to reach equilibrium, and worked with a column 7 mm high. These measurements were stated by Professor de Groot to be still the best measurements that had been made on thermal diffusion in liquid systems.

Dr. Denbigh of Cambridge, in addition to some theoretical speculations, developed a formula for the thermo-osmosis effect which has been tested experimentally with rubber membranes by Miss Raumann of I.C.I., and gives results not in contradiction with the formula, but not precise enough to confirm it.

Mr. Davies of Harwell, who, with Dr. H. Lendon, has been setting up a thermal diffusion column, described the column and its application to several isotope separations. An interesting technique for improving separation of He^3 from He^4 is being investigated which involves the addition of D_2 . This may replace some of the He^4 at the enriched end and since it is easily separated, increases the effective concentration of He^3 .

A paper was also given by Dr. J.M. Agar of Cambridge on the diffusion of electrolytes (at constant temperature) and some remarks were made by Dr. P.M. Marcus on the thermodynamics of the thermomechanical effect in liquid helium II.

I. Review of the Thermodynamics of Irreversible Processes

S.R. de Groot (Utrecht)

General Considerations

The modern form of this subject goes back to work of Onsager in 1931, but parts of it are much older. It has only recently been applied to definite physical and chemical problems.

The title of the subject is somewhat paradoxical because ordinary thermodynamics treats only equilibrium and reversible processes, but tells little about irreversible processes. The difficulty might be avoided by use of the terminology "thermodynamics" for ordinary equilibrium thermodynamics, reserving thermodynamics for non-equilibrium processes.

There exist a considerable number of physical processes which may be described by phenomenological laws but could not be treated from a common point of view without the methods of irreversible thermodynamics. These are essentially steady state processes which are constant in time but are not in equilibrium, such as Fourier's law of heat conduction (heat flow proportional to temperature gradient), Fick's law of diffusion, (mass flow proportional to concentration gradient), Ohm's law, the proportionality of viscous force to velocity gradient, and the proportionality of the rate of a chemical reaction to the affinity. In many cases two such processes occur simultaneously, and then important interaction phenomena occur. The governing relations of such phenomena may be found by the methods of irreversible thermodynamics. Examples of these are thermoelectricity in which heat and electrical currents flow simultaneously, thermal diffusion which is the coupling of the flow of matter and of heat.

Other Methods for Steady State Processes

There are two general methods in addition to irreversible thermodynamics which may be used to study the various steady state processes. The first of these is the statistical or kinetic method of which the best example is the Chapman-Enskog theory of transport processes in non-uniform gases which are not too dense. This method suffers, however, from the disadvantage of being restricted to quite special phenomena. The second method is the so-called quasi-thermodynamical method. This method follows the peculiar procedure of splitting a process into a reversible and an irreversible part and then applies ordinary thermodynamics to the reversible part, while the irreversible parts are neglected. The classical example is the Thomson thermoelectric relations, particularly the second Thomson relation. The transport of

electricity is considered as reversible but the Joule heat is neglected. In the case of thermal diffusion, however, it is not clear whether to treat the flow of matter or of heat as reversible and, in fact, both assumptions have been used. This lack of clarity is a serious defect which may lead to errors.

Irreversible Thermodynamics

Finally, the method of irreversible thermodynamics may be considered, which started with Onsager's work of 1931. Two papers appeared then, the first of which is not quite correct. The second is somewhat easier to read. Casimir has made some small corrections in a paper in 1945. The Onsager theory is essentially a macroscopic theory which does not require all the details of the transport equation of statistical mechanics. The fundamental idea is that of microscopic reversibility. If one looks at the basic equations of physics (Newton's equations, the Schrodinger and Dirac equations), one finds they are invariant to the transformation $t \rightarrow -t$. Onsager proceeded to connect microscopic properties with macroscopic phenomena, and gave a general theorem. This theorem and its applications has since been treated by Belgian, German, American and Dutch workers.

Some of the ideas which guided Onsager in his formulation of the theory are the following:

(1) The special example of heat conduction in anisotropic crystals described by the equation

$$j_i = \sum_{k=1}^3 L_{ik} X_k$$

where x_1, x_2 and x_3 are the components of the temperature gradient in the three directions and j is the flow of heat. The L_{ik} are the conductivity co-efficients which form a matrix of nine quantities. Experimentally, this is a symmetric matrix in which $L_{ik} = L_{ki}$. Voigt and Soret have discussed the heat conduction phenomenon for crystals which do not have a symmetry that would lead automatically to this symmetry property.

(2) Elementary considerations in chemical reactions and in particular the artificial case of the reactions



lead to a similar symmetry property.

Onsager wants to make a connection between macroscopic and microscopic properties using statistical reasoning. He considers the fluctuations of a general statistical system, but no special models or special transport equations. He has to introduce new hypotheses which are, however, also used in Brownian motion theory. These are based on statistical reasoning and microscopic reversibility.

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The Derivation of Onsager's Relations

There are three basic steps in the paper which derives Onsager's relations:

(1) Statistical Theory of Fluctuations

Consider an adiabatically insulated system which is characterized by a number of parameters. Examine the statistical variations of these parameters from their equilibrium values. $\alpha_1, \alpha_2, \dots, \alpha_n$ are these variations. The variation of entropy may then be written $\Delta S = -\frac{1}{2} \sum g_{ik} \alpha_i \alpha_k$ where ΔS is a quadratic and not a linear function of the variations. If P is the probability that a certain set of α 's will be realized, then P is given by the expression

$$P = \frac{e^{\Delta S/k} d\alpha_1 \dots d\alpha_n}{\int e^{\Delta S/k} d\alpha_1 \dots d\alpha_n}$$

Introduce the quantities $\chi_i = \sum_j g_{ij} \alpha_j$. One can then calculate the average to give the result $\alpha_i \chi_j = -k \delta_{ij}$

(2) Microscopic Reversibility

This is an old subject which has been discussed by Ehrenfest and others. The basic relation which is used is the following:

$$\alpha_i(t) \alpha_j(t+\tau) = \alpha_i(t) \alpha_j(t-\tau)$$

This equation expresses the idea that the correlation of α_i at a time t with α_j at a time $t+\tau$ is the same as with α_j taken at a time $t-\tau$. The equation may also be written in the following form:

$$\alpha_i(t) \{ \alpha_j(t+\tau) - \alpha_j(t) \} = \alpha_j(t) \{ \alpha_i(t+\tau) - \alpha_i(t) \}$$

(3) Regression of Fluctuations

This idea is implicit in Onsager's work, but is explicitly brought out by Casimir. Making use of the equation $\chi_i = -\sum g_{ik} \alpha_k$ one writes for the decay of the fluctuations the equation

$$\dot{\alpha}_i = -\sum_k L_{ik} \alpha_k$$

This decay goes in the same way as the decay of macroscopic fluctuations. One should write more precisely, however, the following equation $(\alpha(t+\tau) - \alpha(t)) / \tau = \sum L_{ik} \alpha_k$; $\tau_0 \ll \tau \ll \tau_R$ where τ_0 equals the time between two collisions and τ_R is the relaxation time or decay time of the fluctuations.

Combining Part III with Part II leads to the following

equations: $\alpha_i(t) \sum_k L_{ik} \alpha_k = \alpha_j(t) \sum_k L_{jk} \alpha_k$; $-k \sum_k L_{jk} \delta_{ik} = -k \sum_k L_{ik} \delta_{jk}$

from which the reciprocal relations $L_{ji} = L_{ij}$ follow.

In a magnetic field the Lorentz force on a charged particle is $F = e[\vec{v} \times \vec{H}]$. Now if one wants to reverse the velocities one must reverse the magnetic field H as well. Therefore, if α is a function of H, one must replace H by -H, and obtain the Onsager relation in the form $L_{ji}(H) = L_{ij}(-H)$. Casimir found this relation in an experiment on electrical conduction, namely by considering the Hall effect and the conductivity tensor. One also obtains the relation $L_{ii}(H) = L_{ii}(-H)$

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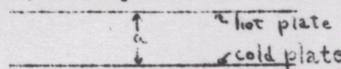
A similar result is obtained in the theory of the heat conductivity tensor.

It should be remarked that the quasi-thermodynamic treatment of steady state processes does not lead to an effect of a magnetic field.

II. Introduction to Experimental Work in Irreversible Thermodynamics

S.R. de Groot

The process of thermal diffusion will be used to illustrate the experimental work in this field. This process takes place in gases, liquids and even solids. It may be described as follows: material is contained between two plates, a hot plate above and a cold one below. When there are two components in the system a migration of matter occurs and a concentration gradient is set up as a result of the temperature gradient. In the present case, both gradients are along the vertical. This concentration gradient gives rise to ordinary diffusion which tends to make the mixture homogeneous again. A steady state is eventually reached in which there is no flow of matter but a flow of heat.

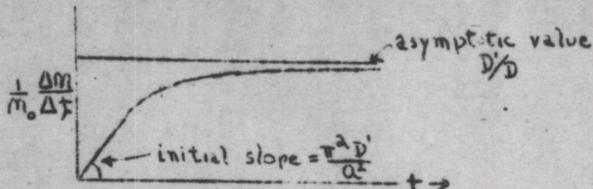


The phenomenon has a curious history. It was first found by the German physicist Ludwig (1856) and some time afterwards by Soret. In English usage the effect in liquids and solids is called the Soret effect, whereas the Germans call it the Ludwig-Soret effect. In 1857 Thomson discovered thermo-electricity which is essentially the thermal diffusion of electrons in a solid and may be described in the same way. The effect was overlooked in gases, however, apparently because Maxwell's special model of a gas which assumed a fifth power repulsion law between the molecules gave no thermal diffusion phenomenon. It was found theoretically in gases by Enskog in 1911 and by Chapman in 1917, who also gave some experimental evidence. Recently, the general subject has been revived by Clusius and Dickel with their thermal diffusion column for the separation of isotopes. One grave difficulty in the experimental work was that it was not realized how long it takes for the steady state to be reached, especially by the older experimenters.

The following phenomenological equation describes the process in the system above: $J = -D \frac{\partial n}{\partial x} - D' n \frac{\partial T}{\partial x}$ where J is the flow of matter; the first term on the right expresses Fick's law of diffusion and D is the diffusion coefficient; the second term on the right is the thermal diffusion term and D' is the thermal diffusion coefficient. If we add to this the equation of continuity $\frac{\partial n}{\partial t} = -\text{div } J$ then these equations may be solved with appropriate boundary conditions to give the behavior of the system. The following diagram illustrates the behavior and shows the exponential approach to the

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final steady state.



Here, Δn is the difference in concentration between the hot and the cold part and n_0 is the original concentration of one component. The final formula is $(1/m_0) (\Delta m / \Delta t) = (D'/D) (1 - e^{-t/\theta})$ where $\theta = \alpha^2 / \pi^2 D$ is the characteristic time.

If the vessel is too large it takes a very long time to reach the steady state. It is worth noting that information is obtained both from the steady state value which gives $\frac{D'}{D}$ and from the initial slope which gives D' directly.

Kinetic theory has been extensively applied in connection with this phenomenon. It is contained implicitly in the work of Chapman and Cowling. The co-efficients D and D' may be calculated from the methods of Chapman and of Enskog if one assumes a certain intermolecular force expression. The Lennard-Jones model has been selected as the one nearest reality with which the calculations are still possible. This expression has the form of the difference of two inverse powers of r ; the higher power (usually 12) is a repulsive term, the lower power (usually 6) a longer range attraction. The diffusion co-efficient, the viscosity co-efficient, the heat conductivity co-efficient may then be calculated when some form of the Lennard-Jones formula is assumed and the experimental values are reasonably well satisfied. The thermal diffusion co-efficient, however, or the ratio $\alpha = \frac{D'}{D}$ is not verified experimentally. The same accuracy is not attained in the calculation of α as in the calculation of D since α is more sensitive to the exact nature of the force curve. Calculations of the thermal diffusion co-efficient have also been made by Furry and Jones for a Lennard-Jones potential with exponents 8 - 4 and 4 - 2 and K.E. Grew has done the case 9 - 5.

The reverse effect must also exist in which a concentration gradient is given and a temperature difference is produced. This was found in gases some 80 years ago and should be called the Dufour effect, although Clusius and Waldman call it their effect. It is difficult to observe since it dies out in time. The Dufour effect in liquids has not been found. This is more difficult because the heat of mixing interferes.

It is of interest to compare the co-efficient $\alpha = \frac{D'}{D}$ in the Soret effect for liquids and for gases. Surprisingly, the magnitudes may be the same since typical figures give $\frac{D'}{D} = \frac{10^5}{10^5} = 1$ for gases and $\frac{D'}{D} = \frac{1}{1} = 1$ for liquids. The separation in liquids might be even higher than in gases.

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However, the Dufour effect which depends on D^1/λ ($\lambda = \text{heat conductivity}$) is much larger in gases where the ratio $(D^1/\lambda) = 10^8 = 10^5$, whereas in liquids it is approximately 1. Hence

if the temperature difference produced in a gas by a concentration gradient is of the order $0.1^\circ - 1^\circ$, in a liquid it would be very small indeed.

The possibility of electrical effects due to temperature gradients also exists, when one considers a mixture containing an electrolyte. An electrical potential gradient is set up by a temperature gradient. However, a concentration gradient also sets up an electrical potential gradient, the ordinary diffusion potential, which is of the same magnitude. Since such a concentration gradient is also induced by the temperature gradient, the two effects must be separated in the measurements.

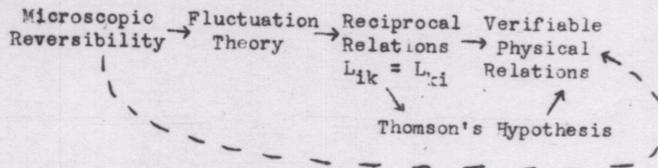
III. Thermodynamics of the Steady State - K.G. Denbigh (Cambridge - Chemical Engineering Department)

This paper was concerned with an attempt to put the theory of the steady state into a simpler form. The overall objective was to obtain the observed quantities directly from the principle of microscopic reversibility.

First, the hypothesis due to W. Thomson (1850) was recalled which considers a system in a stationary state (but not a true thermodynamic equilibrium). This means that the macroscopic parameters are time independent. Now if in this system a particular process J has come to an end (e.g. diffusion) then a virtual fluctuation ΔJ will create no entropy although other processes are still going on.

This same hypothesis was used by Helmholtz and Nernst in the treatment of diffusion potential and the E.M.F. of the concentration cell. Later Eastman and Wagner applied it to the Soret effect and London applied it to the fountain effect in He II. Although the predicted relations were generally confirmed by experiment, the hypothesis was not known to be based on any deeper physical principle.

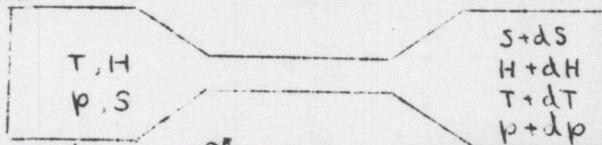
Finally, Onsager in 1931 gave a theory of the steady state which is based on microscopic reversibility as a fundamental principle. From a complex fluctuation theory argument the same verifiable physical relations are obtained as by Thomson's hypothesis and, in fact, the latter may also be derived. The following schematic representation of the different parts of the theory indicates their relationships:



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Onsager's theory is limited to cases where the rates are linear functions of the thermodynamic forces, which seems to be true only close to equilibrium. The Thomson hypothesis, and the verifiable physical relations may, however, be independent of this linearity. If they do have this greater generality it would be of great interest to establish it. An attempt has been made to obtain the physical relations directly from microscopic reversibility following the dotted line in the diagram.

The following diagram illustrates a thermo-osmosis system which has two vessels at different temperatures and pressures containing a single pure substance and communicating through a porous plate



The relation $dp/dT = -Q^*/vT$ may then be derived either from Thomson's hypothesis, from the Onsager theory, or by a direct calculation from microscopic reversibility, where Q^* is the heat of transport through the porous plate, etc., and v is the molar volume of the fluid.

The equation may also be written in integrated form as follows: $\log_e \left(\frac{p_2}{p_1} \right) = \frac{Q^*}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)$ and compared with experiment.

A following paper by Miss Raumann discusses this comparison.

IV. Experiments on Thermo-Osmosis Through a Membrane - G. Raumann,
(Butterwick Research Laboratory)

Experiments are underway at the Butterwick Research Laboratory of Imperial Chemical Industries on thermo-osmosis of a gas through various rubber membranes. The purpose of the work is (1) to demonstrate the presence of the effect, (2) to verify the law derived from theory, i.e. $\ln(p_2/p_1) = \frac{Q^*}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)$

where p_1, p_2 and T_1, T_2 are the pressures and temperatures of the gas on the two sides of the membrane, and Q^* is the heat of transport, (3) to obtain relative values of Q^* , (4) to obtain absolute values of Q^* .

The equipment consists of two thermostatted tanks, in which are immersed the metal gas holders. The latter are in contact with a rubber membrane. The gas reaches the membrane only over a very small area while the rest of the membrane surface is in contact with metal at the proper temperature for each side. The temperatures are measured very near the membrane surface by thermocouples inserted in holes drilled nearly to the face of the metal. Pressure measurements in the two gas-holders are made with manometers.

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To show that one is not observing a mere heating effect which increases the pressure on one side, the gas-holders can be connected to a U-tube and gas continually bubbles through from the hot side to the cold side. One can also show that this is not a case of thermo-effusion since one finds with H_2 the effect has the opposite sign to CO_2 . Also the final values of $\frac{p_1}{p_2}$ may be approached in time both from above and below.

Plots of the final value of $\frac{p_1}{p_2}$ against $1/T$ with the data so far obtained are not in disagreement with the law above, but do not as yet confirm it. If the value of Q^* for CO_2 is 100, then for N_2 it is +19 and for H_2 is -17. These values do not correlate with the heats of solution of the gases in natural rubber, and so other quantities may affect Q^* .

A new apparatus is being designed to eliminate some of the chief difficulties with this one, namely, that the gas is not uniformly distributed over the membrane, and the heat flow is not perpendicular to the membrane. Also, it is assumed that the temperature of the membrane is that of the plate next to it. Now the gas will pass into porous blocks of metal to be distributed over the entire surface, and the block will be surrounded by a gas gap to make the heat flow perpendicular. Thermocouples will be inserted into the porous metal and the temperature at the surface will be calculated but holes will not be drilled which would disturb the heat flow.

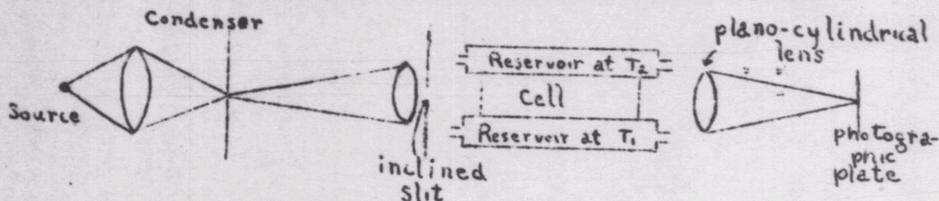
V. Thermal Migration - The Soret Effect by C.C. Tanner (Imperial Chemical Industries)

The Problem and Difficulties

From 1924 - 1927 a set of experiments was performed by Dr. Tanner which studied the phenomena of the Soret effect. This effect concerns changes in concentration set up in a condensed liquid system under the constraint of an imposed temperature gradient. The method applied at that time was quite successful in obtaining useful data and might very well be applied again. (In his lectures Professor de Groot referred to this work as the best in the field to date). Since the Soret effect is a diffusion process which requires a length of time to reach equilibrium varying as a square of the effective length of the apparatus, this length must be made as short as possible. With the long tubes used by early experimenters some 500 to 1000 hours were needed to reach a steady state, and frequently, of course, this was not attained. In the apparatus actually used, however, the length was reduced first to 9 mm and eventually to 7 mm. Today it should be possible to reduce the length as far as 3 or 1 mm. One must also design the apparatus for measurements of concentration as a function of height which does not involve removing samples from the cell for analysis.

The Method and Apparatus

The method applied was to measure the refractive index gradient in the cell containing the solution by observing the deflection of a horizontal parallel beam of light transmitted through the cell. The diagram illustrates the experimental arrangement.



The angular deviation of the light beam was proportional to the length of the light path through the cell solution and to the refractive index gradient with height. Angles measured were less than 1/10th radian. The light passed through a slit inclined to the vertical and was then focussed by a cylindrical lens which also turned the image to a horizontal position. Distance along this horizontal line corresponded to height. One constructional difficulty that could probably be met more easily today concerns the junction of the optical glass walls and metal. The glass-metal joint had to be made to avoid cracking when warmed up. Black picene was used to seal the glass into recessed flats of metal.

The Experimental Technique

The experimental technique is first to bring the cell to equilibrium at the lower temperature and obtain the reference position of the horizontal straight line formed by the light beam. The temperature of the upper wall is then raised to its final value and in about five minutes the line shifts to the inclined position characteristic of the variation of the refractive index with temperature. The value of the line for pure water may be obtained to check the instrument constants. A primary difficulty is now to separate this temperature effect on the refractive index from the concentration changes one wishes to measure.

For solutions the line of light now continues to shift as diffusion changes the concentration c at various heights in the cell hence modifies the refractive index gradient. The deviation of the light at any height from the line produced by the thermal dependence of refractive index now measures the refractive index gradient at that height produced by the concentration change. Integration gives the total difference in refractive index between top and bottom of the cell, from which the concentration difference may be obtained. Thus the temperature effect is separated from the diffusion effect. Since the former was relatively large, the experiments were confined to relatively concentrated solutions, usually greater than molar, except where $\frac{du}{dc}$ (u = refractive index) was exceptionally large.

The final steady state could take as long as 24 hours using temperature differences of 10 - 15° over a cell height of 7 mm. The first diffusion changes were most rapid, however, and exposures of the line of light were taken at one minute intervals over the first five minutes, and then at longer intervals.

Results

The results obtained showed rather irregular variations for moderately concentrated salt solutions, acids or bases, the magnitude of the effect being 1 molar % change in concentration per degree centigrade. Some solutions, however, (e.g. LiCl, CaCl₂, MgCl₂, NH₄Cl) were anomalous in not showing drift in refractive index with time.

VI. The Thermal Diffusion Column at Harwell, by R. Davies - (Harwell)

A thermal diffusion column has been set up at Harwell and applied first to the separation of zirconium and hafnium using the tetrachlorides, and then to the separation of O¹⁸ using water vapor. The column is 8 feet long, the central platinum wire is maintained at 1000°C, and the walls at about 150-200°C.

In the water vapor experiments, the O¹⁸ is not found where expected, but the H₂O¹⁸ molecules are found at the top of the column corresponding to an exponent ν in the force law for water molecules of less than 5 (approximately 4.9). The water vapor is at 1 atm. pressure in the column.

In applying the column to the separation of He³ from He⁴ an idea is being developed that may appreciably improve the separation. This is, namely, to let into the column near the upper part a small amount of D₂ (molecules of which have the same molecular weight as He⁴). Then an analysis of the three component system, provided the separation factors are in the proper order, may show a blanket of D₂ between the He³ and the He⁴. For example, one might find at the top of the column instead of 1% He³ and 99% He⁴, 1% He³, 50% D₂ and 49% He⁴. The D₂ is then easily separated out and the concentration of He³ correspondingly increased.

APPENDIX A

LIST OF PEOPLE ATTENDING CONFERENCE ON
THERMODYNAMICS OF IRREVERSIBLE PROCESSES
5th and 6th JANUARY 1950

Butterwick Research Laboratory,

I. C. I.

Mr. M. T. Sampson
Dr. H. Kolsky
Mrs. M. J. Moore
Miss G. Raumann
Dr. K. W. Hillier

I. C. I. Head Office & Divisions

Dr. F. A. Freeth, Head Office
Dr. R. le G. Burnett, General
Chemical Division
Mr. A. G. M. Hedley, Alkali Division
Mr. C. H. Besanquet, Billingham
Mr. P. Davies, Billingham
Dr. C. C. Tanner, C.A.C.

British Rubber Producers' Research
Association

Dr. G. Gee
Dr. R. S. Rivlin

Harwell

Dr. H. London
Mr. R. H. Davies

Cambridge

Mr. P. D. Mitchell, Dept. of
Biochemistry
Mr. R. E. Danckwartz
Dr. H. Gutfreund, Dept. of
Colloid Chemistry
Dr. J. M. Agar, Sidney Sussex
College
Dr. K. G. Denbigh, Dept. of
Chemical Engineering

Oxford

Dr. G. S. Rushbrooke

Holland

Prof. A. M. J. F. Michels,
Amsterdam
Mrs. Michels
Prof. S. R. de Groot

Office of Naval Research,
American Navy

Dr. P. M. Marcus

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