RHEOLOGY BULLETIN

CONSTITUTION REVISIONS

PUBLICATION OF THE

SOCIETY OF RHEOLOGY

VOLUME 18, NO. 2 JUNE, 1947

RHEOLOGY BULLETIN

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TABLE OF CONTENTS

Change in date of issue 3

Revision of the Constitution and By-Laws 3

Suggested Revisions of the Constitution and By-Laws. 4

Bingham Memorial Award 6

Treasurer's Report 7

Nomination of Officers, 1948-1949 7

British Rheologists Club—Nomenclature 8

Ballot on Constitution and By-Laws Revisions 13

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Rheology Bulletin

Publication of the Society of Rheology

Vol. 18, No. 2 June, 1947

Change in Date of Issue

HEREAFTER the Bulletin will be dated March, June, September, and December instead of February, May, August, and November. This change has been made for the following reasons:

1. September permits more details of the coming Annual Meeting than does August.
2. December covers the Annual Meeting sooner than February (the November deadline does not permit coverage).

Revision of the Constitution and By-Laws of the Society of Rheology

THE necessity for changes in the constitution and by-laws of the Society have been presented in past issues of the Bulletin and at the 1946 meeting. After a quantity of correspondence and two meetings, the president of the Society and the committee appointed to draw up proposals for this purpose offer the suggestions presented in this number for your judgment. The present constitution and by-laws may be found in the May, 1946 issue (Bingham Memorial Edition) of the *Rheology Bulletin*. New members who do not have access to that number may obtain a copy of the constitution and by-laws from the secretary. A ballot to indicate your approval or disapproval of the suggested changes will be found on the last page of this issue.

If you disapprove of any or all of the proposals, please submit your own proposals to replace those you disapprove. Those proposals that a majority of the members does not approve will be stricken from the amendments until a majority agreement is reached—*provided* the ballots of a majority of the members are accompanied by suggested changes.

Those members not voting will be counted as favorable to all the proposed amendments printed in this issue.

If the proposed amendments are accepted by the members, the complete, revised constitution and by-laws will be published in the September number of the Bulletin.

Committee on Constitution and By-Law Amendments,

TURNER ALFREY, JR.
R. B. DOW
W. H. MARKWOOD, JR., *Chairman*

Suggested Revision of the Constitution and By-Laws of the Society of Rheology

CONSTITUTION

Article I—Name

Do not change present statement.

Article II—Purposes

Present statements adequate, except for (b) which should read: "By sponsoring publications designed to increase and disseminate knowledge of rheology."

Article III—Membership

Substitute "purposes" for "objects" in first sentence. Delete: "with the endorsement of two active members." In last sentence, replace "Article II" by "Article III."

Article IV—Officers

Omit: "Publishing Editor"; also: "Adopted Pittsburgh December 27, 1933." Change: Secretary to Secretary-Treasurer. Delete all of present Section 2. See Article V below. Change Section 3 to Section 2.

Article V—Executive Committee

Replace Article V by the present Section 2 of Article IV. Present Article V to become Article VIII, with revisions.

Added Articles

Article VI—Meetings

"An annual meeting of the Society for the purpose of holding technical sessions or symposia, and to transact business shall be set each year by the Executive Committee which shall announce the time and place at least six months prior to the meeting. Additional technical meetings may be held as shall be determined by majority vote of the Executive Committee."

Article VII—Reports

"The Secretary-Treasurer of this Society shall report annually in writing to the membership at the Annual Meeting in respect to the activities and the financial condition of the Society. Publication of the abstracts of these reports, setting forth the pertinent facts about the operation of the Society, shall satisfy the requirements of the membership.

"The Executive Committee shall have the authority to make any other reports it considers advisable, or as may be requested by a legitimate agency or institution, or as may be required by the civil law."

Article VIII—Amendments to Constitution

Change "two-thirds vote" in present Article V to read: "Majority vote."

Strike out all following "to the membership" and add "after the members attending a regular meeting of the Society, or the Executive Committee have voted to submit such amendments to letter ballot. The votes on the amendments shall be canvassed within ninety days after their origin. Said amendments shall become effective immediately upon certification of approval by the Secretary-Treasurer to the Executive Committee."

BY-LAWS

Article I—Duties of Officers and Executive Committee

Replace present Article I with:

Section 1

"The President of the Society shall exercise general care and supervision over the affairs of the Society subject to the direction and approval of the Executive Committee, and shall do and perform all acts usually incident to the office of President.

"The President shall preside as Chairman at the meetings of the Executive Committee, except that in the absence of the President a Chairman pro tempore shall be chosen by the Committee."

Section 2

"The First and Second Vice Presidents shall take precedence in their respective order. If for any reason, the office of President shall become vacant, the Vice Presidents shall succeed in office according to rank.

"They shall, under the direction of the President, oversee the functioning of such committees as may be active in the Society."

Section 3

"The Secretary-Treasurer shall keep the records of the Society, including minutes of all meetings, appointments, committees, and membership files.

"He shall be responsible for the correspondence of the Society in regard to its ordinary and general matters of business.

"He shall prepare an annual report of the activities of the Society in accordance with Article VII of the Constitution.

"He shall be responsible for the printing, distribution, and collection of letter ballots which may be presented to the membership for vote. In particular, he shall be charged with the issuance and receipt of the ballots for the membership vote on officers as defined in Article IV of the By-Laws and for the issuance and tabulation of ballots on proposed amendments to the Constitution and By-Laws as specified in Article VIII of the By-Laws, respectively.

"He shall receive all monies of the Society and deposit the same in a recognized bank in the name of the Society.

"He shall be the disbursing officer of the Society and shall sign all checks and vouchers for expense incurred by the Society upon authorization of the Executive Committee.

"He shall give bond for the faithful discharge of his duties, to the extent as may be required by the Executive Committee.

"He shall prepare an annual report on the state of the finances of the Society in accordance with Article VII of the Constitution."

Section 5

"The Editor shall be responsible to the Executive Committee for carrying out the publication policy of the Society.

"He shall have the technical direction of the Society's publications, as defined in Article VI of the By-Laws."

Section 6

a. The present Section 1 of Article IV. Change last sentence to read: "All rules and regulations so made shall terminate with the expiration of tenure of office of the officers responsible for promulgating them, unless continued by incoming officers constituting the succeeding Executive Committee."

b. The present Section 7 of Article II, with the following addition: "The Vice Presidents shall succeed the President as stipulated in Section 2 of Article I of the By-Laws."

c. "The Executive Committee shall have authority to recommend the acceptance of gifts or memorials for the Society, providing a majority vote of the Committee affirms the action. Such gifts shall be accepted by the Society upon a majority vote of the membership in attendance at a regular meeting of the Society unless opposed by a majority of the whole Society as represented by their personally appointed proxies at the next regular meeting after offer of said gift.

"The Executive Committee shall authorize all expenditures and shall not create any indebtedness beyond the means of the Society, nor disburse funds for purposes nonessential to the business or purposes of the Society.

"It shall determine the date and place of the annual meeting and any other meetings of the Society which shall be called in accordance with Article VI of the Constitution.

"The Executive Committee shall hold regular meetings, preferably semiannually, to consider the business of the Society, such meetings to be called by the Secretary in accordance with previous action of the Committee on authorization of the President, or on written request of a majority of the Committee members.

"Notices of meetings of the Executive Committee shall be given to each member at least ten days prior to the date of the meeting.

"A majority vote of the Executive Committee shall govern, except where otherwise provided.

"The Executive Committee shall have the power to overrule or modify the action of any officer of the Society."

Article II—Dues and Privileges

Replace present Article II with:

Section 1

"Regular members of the Society shall pay annual dues of $4.00, payable in advance, if resident of the United States or Canada, or $4.40 if resident elsewhere. Each member shall be entitled to subscription to the official publications of the Society."

Section 2

"Sustaining members shall pay dues of $25.00 annually as a minimum, payable in advance, and shall be entitled to subscriptions to the *Journal of Applied Physics* and the *Review of Scientific Instruments*, in addition to the official publications of the Society.

"A sustaining member may appoint a representative to act for it at meetings of the Society."

Section 3

"Regular and sustaining members of the Society in good standing shall be elected to corresponding membership in the American Institute of Physics without payment of additional dues."

Section 4

The present Section 3-A of Article II with the change "coming year" to "current year" and with the following addition: "Members delinquent in dues three months after the official date of renewal shall be declared suspended and their names removed from the official roster of the Society. Suspended members may be reinstated within a period of two years by payment of back dues; thereafter, applications for reinstatement shall be referred to the Membership Committee."

Article III—Membership Committee

Replace present Article III with: The present Section 4 of Article II with the insertion of "at least" before "three."

Article IV—Nominating Committee

Replace present Article IV with: The present Section 5 of Article II, except for the following changes:

1. First paragraph, replace "three members" by "at least ten members."
2. First paragraph, second sentence, change "nine months" to read "six months."
3. First paragraph, last sentence, change "six months" to read "four months."
4. Second paragraph, first sentence, replace "three" with "two."

Article V—Representatives

Section 1

"As a Member Society of the American Institute of Physics the Society shall be entitled to nominate candidates for directorship on the Governing Board of the Institute, to the number of and under the circumstances authorized by Article VIII of Amendment No. 1 of the Constitution of the American Institute of Physics Incorporated.

"On the basis of a membership census the Society shall elect one director to the Governing Board of the American Institute of Physics who shall be the President of the Society, or his officially appointed representative.

"When the membership of the Society attains such a number as to entitle it to more directors on the Governing Board of the American Institute of Physics they shall be, in order, the Secretary-Treasurer, the Editor, the First Vice President, and the Second Vice President or proxies appointed by the President in their absences.

Section 2

"The terms of office of directors representing the Society on the Governing Board of the American Institute of Physics shall be set for two year periods, concurrent with their terms of office in the Society."

Section 3

"The President shall appoint the Society's representative to the Council of the American Association for the Advancement of Science, on the basis of its membership as an Affiliated Society of Section B, Physics, of the A.A.A.S.

"The President shall appoint an official representative of the Society to attend technical meetings, inaugurations or dedications. Upon recommendation of the President, the Executive Committee shall determine the expense allowance of official representatives."

Article VI—Publications

Section 1

"Technical papers presented to the Society for publication shall, after approval by the editor, be submitted by the editor to a journal recognized by the Society as an official organ of the Society for publication in such journal."

Section 2

"The Society shall publish or choose a publication which shall officially contain news of the Society and other matters of rheological interest."

Section 3

"The Editor shall have the authority to appoint assisting, contributing, and publishing editors to be responsible for the development of the different aspects of the publications of the Society."

Article VII—Affiliated Sections

The present Section 1 of Article I.

Article VIII—Amendments

"The By-Laws may be amended by majority vote of the members returning a letter ballot after the members attending any regular meeting of the Society, or the Executive Committee, have voted to submit the proposed amendment to letter ballot. The votes on the amendments shall be canvassed within ninety days after their origin. Said amendments shall become effective immediately upon certification of approval by the Secretary-Treasurer to the Executive Committee."

Bingham Memorial Award

Although the Executive Committee has been working diligently on the steps required for the foundation of an annual award in rheology, it is unlikely that the Society will be in a position to award a medal in 1947, but not entirely inconceivable. One will definitely be awarded in 1948, however.

President Fair has worked hard in obtaining information from various medal designers and manufacturers and in soliciting contributions from the members of industry interested in the advancement of the science. To date a particular designer and manufacturer have not been selected, but probably will be in the near future. As of May 13 approximately $1500 had been received. It is estimated that about $2500 will be required to make the project indefinitely self-sustaining.

The Executive Committee has not yet appointed an award committee although it has a large number of members under consideration, none of whom are members of the Executive Committee.

Donors to the fund as of May 13 are:

Mrs. E. C. Bingham
Barrett Division, Allied Chemical and Dye
Bristol-Meyers Company
Carbide and Carbon Chemicals Corporation
Celanese Corporation
Corning Glass Company
Gulf Oil Company
Hercules Powder Company
Interchemical Corporation
Johns-Manville Company
Koppers Company
A. D. Little Company
Monsanto Chemical Company
Standard Oil Company of New Jersey
Swan-Finch Oil Corporation
The Texas Company
United Sanitary Corporation

Society of Rheology

Treasurer's Report—1946

Balance on hand December 31, 1945		$530.81
Income		
Membership dues	$578.00	
Back dues	12.00	
		590.00
Subscriptions to Bulletin	85.80	
Back sales of Bulletin	143.01	
		228.81
Registration Annual Meeting		134.00
Total		$952.81
Expense		
Bulletin		
May issue	$164.98	
August issue	109.01	
November issue	110.39	384.38
American Institute of Physics overhead, current expense, mailing		
First quarter	22.83	
Second quarter	24.53	
Third quarter	20.28	
Fourth quarter	23.18	
		90.82
AIP 15% assessment (1945 membership)		62.10
Miscellaneous		
Stationary	17.50	
Postage	7.57	
Membership cards	7.25	
Loss on foreign subsc.	.50	
Program expense	1.95	
Mrs. E. C. Bingham	9.52	
Annual Meeting (Hotel Pennsylvania and party)	90.98	135.27
Total		$672.57
Net Balance 1946		$280.24
Total cash on hand December 31		$811.05

Nomination of Officers for the Two-Year Term 1948–1949

For President .... W. F. Fair, Jr.
For First Vice President .... H. M. Spurlin
For Second Vice President .... R. N. Traxler
For Secretary-Treasurer .... E. K. Fischer
For Editor .... W. H. Markwood, Jr.

Nominating Committee

R. B. Dow, *Chairman*
A. Nadai
H. K. Nason
R. S. Spencer.

British Rheologists Club

NOMENCLATURE

LAST spring the editor of the *Rheology Bulletin* received a copy of the following committee report from England. It is believed to be as complete a discussion of rheological nomenclature as appears anywhere in the literature. As such, it is of prime importance to all members of the Society, which is the reason for its publication here. You may find that some of the concepts differ from your own. Consequently, criticism and discussion are welcome and will be published in a later *Rheology Bulletin* as well as forwarded to our British colleagues. This report is reprinted through the courtesy of Professor G. W. Scott Blair, editor of the bulletin of the British Rheologists Club.

The Meaning and Use of Certain Rheological Terms

Report by the Committee of the British Rheologists' Club

Dr. Mardles, R.A.E.

1. GENERAL INTRODUCTION

In any discussion of nomenclature, certain difficulties are continually recurring. Of these the most serious are probably (1) the use of the same term in different senses in different sections of a science, and (2) the use of terms which have a general or qualitative everyday meaning, as well as a quantitative scientific significance. Nomenclature in rheology encounters not only these general difficulties, but also another kind of difficulty characteristic of a newly developed subject, namely, that many of the phenomena with which it is concerned are themselves frequently not sufficiently well understood to be unambiguously defined and classified.

This paper is an attempt to clarify certain terms and concepts, to point out the nature of any confusion which may have attended their usage, and when possible, to suggest means whereby such confusion may be avoided. At the present stage it would be too much to hope for finality or completeness, and the suggestions put forward are intended mainly to provide a basis for further discussion and development.

In the selection of terms, the Committee recommend the adoption of the following three guiding principles:

Principle 1.—Terms should be related as directly as possible to phenomena which are observable (or in principle observable), rather than to theoretical constructions or analytical interpretation of phenomena.

Principle 2.—Whenever possible, terms should be either self-explanatory, or designed to convey some indication of their meaning (directly or etymologically).

Principle 3.—Words commonly employed in an everyday or semi-scientific sense should not be given a quantitative connotation. They may, however, be retained as qualitative terms when they can be shown to fulfill a definite need.

It is emphasized that these are only *guiding principles*, not absolute rules, and there may well be exceptional cases in which the choice of suitable terms may be governed by other considerations. Thus, for example, the term "Hookean elasticity" is justified by the almost universal familiarity with Hooke's law, so that it is in effect self-explanatory, even though it does not conform literally with the second of our principles. Again, terms like *force* and *energy*, though used in a loose sense in everyday speech, have nevertheless a well-defined quantitative meaning in mechanics. This double usage does not appear to lead to confusion, because of the wide difference between the general and the scientific meanings.

Other cases may be quoted, however, in which the position is not so happy. Two such cases are worthy of special consideration:

(a) *Consistency*

With regard to the word *consistency* the (American) Society of Rheology have proposed two usages, (1) qualitatively, as "the resistance to deformation," and (2) quantitatively, as "the ratio of shear stress to rate of shear," when this ratio is not constant.

The Committee feel that the use of the term in these two different senses is a source of confusion, and propose that it should be restricted to the first, or qualitative usage.

(b) *Stiffness*

The term *stiffness* has been used not only in a qualitative sense, meaning rigidity or resistance to deformation, but also in several different quantitative senses, *viz.* (1) as reciprocal of, "mobility" in Bingham flow, (2) as the quantity constant in the Nutting equation, by Buist and Seymour, (3) as rigidity modulus, or closely-related quantity.

Whilst drawing attention to the present position, the Committee do not feel able to recommend a solution to the difficulty without further discussion.

2. SYSTEMS OF CLASSIFICATION

Terms cannot be considered in isolation, on account of the relations which they bear one to another. Inevitably, therefore, nomenclature implies some system of classification. In this section we consider some of the systems of classification which have been put forward.

(a) The British Rheologists' Club's "Table of Deformations"

A scheme of classification was put forward by the B.R.C. originally in 1942, and in a modified and more convenient form later in the same year. The later form is reproduced in Fig. 1. [This figure was not received—*Ed.*] Based generally on the principles enunciated in the preceding section, this scheme is largely self-explanatory. It is worth noting that only *deformations* are dealt with; no attempt was made to introduce real materials or types of matter. This limitation appeared to be advantageous, at least in a first attempt, in that it avoided the difficulty that a real material is generally capable of a diversity of types of behavior according to the conditions under which it is examined (e.g., pitch, glass, rubber).

Bilmes' variation of the Table

A circular layout of the B.R.C. Table has been proposed by Bilmes. His arrangement involves no intrinsic departure from the original classification, but may have advantages in a more effective pictorial presentation of the relationships between the types of deformation.

(b) Reiner's System of Classification

A rather different approach has been suggested by Reiner. In his system a number of characteristic "bodies" are defined. These "bodies" are defined in terms of their law of deformation, so that in effect the definitions may be regarded as definitions of types of deformation. The following five fundamental bodies are distinguished:

E. *Euclid solid.* A perfectly rigid (i.e., non-deformable) body. P. *Pascalian liquid.* A perfectly non-viscous fluid.

H. *Hooke solid.* A body which gives a Hookean elastic deformation.

ST. V. *St. Venant body.* A body characterized by the existence of a yield stress (and which presumably behaves like E at lower stresses and like P at higher stresses).

N. *Newtonian liquid.* A body which is capable of a Newtonian viscous deformation.

Types E and P have no real counterparts in rheology, and need not be further considered. The remaining three may be combined in various ways to produce more complex types of deformation. The three principal derived types are:

M. *Maxwell liquid.* This is represented H and N in series. (Spring and dashpot in series.) This is a special case of the B.R.C. Viscoelastic deformation.

B. *Bingham body.* Defined as ST. V and N in series. This is equivalent to the B.R.C. Bingham plastic deformation.

K. *Kelvin solid.* Defined as H and N in parallel. (Spring and dashpot in parallel.) This is a special case of the B.R.C. Non-ideal completely recoverable deformation.

By further combinations between the fundamental and derived types still more complicated properties may be represented. The properties of all these bodies may be represented by means of rheological equations, the parameters in which correspond to the values of certain physical constants.

It is not proposed here to make any judgment on the relative value of Reiner's and the B.R.C. schemes, but it may not be out of place to make some reference to the underlying divergences in the respective methods of approach. We observe, firstly, that Reiner's system is based on the assumption that the behavior of a given system can be represented in terms of a number of elements, each obeying a simple law. This theoretical analytical approach is in contrast to the empirical approach of the B.R.C., represented Principle (1). Secondly, Reiner's terms are not self-explanatory, but are all associated with the names of original investigators.

(c) The Nomenclature of the Dutch School

Burgers, Saal, and Bienzeno have published (in Dutch) a rather comprehensive report entitled "Basis for a Nomenclature of Deformations,"[1] which attempts to cover the whole range of types of deformation. It is hardly possible to convey an adequate idea of the scope of this work in summary form, but it may be said that the method of approach is identical in principle with that adopted by the B.R.C., though there is naturally some difference in emphasis and in detailed terminology. The following table contains a list of the principal types of deformation considered, together with the most nearly comparable B.R.C. types.

Types of Deformation

	Dutch System	Nearest B.R.C. Equivalent
A0	Completely elastic deformation	TIdeal elastic deformation TNon-ideal completely recoverable
A1*a*T A1*b*T	Thresholdless limited deformation	Non-ideal completely recoverable
B1*a*T B1*b*T	Plastic limited deformation	Plasto-elastic deformation (?)
A2	Thresholdless creeping deformation ($d‡/dt$ continually decreasing)	Non-Newtonian viscous flow (special case)
B2	Plastic creeping deformation ($d‡/dt$ continually decreasing)	Non-Bingham plastic flow (special case)
A3	Thresholdless constant speed deformation ($d‡/dt$ const.)	Newtonian flow
B3	Plastic constant speed deformation ($d‡/dt$ const.)	Bingham flow
A4	Thresholdless accelerating deformation ($d‡/dt$ increasing)	Non-Newtonian viscous flow (special case)
B4	Plastic accelerating deformation ($d‡/dt$ increasing)	Non-Bingham plastic flow (special case)

The general similarity between the two systems is apparent from this table. Apart from the actual terms used, the chief difference is that the Dutch system contains rather more subdivisions of the flow group, and rather fewer of the elastic group than the B.R.C. classification.

We turn now to the consideration of certain terms and phenomena in greater detail.

3. STRESS, STRAIN, AND RELATED QUANTITIES

Since stress and strain are fundamental quantities in all rheological measurements, it may be well to begin the discussion by a consideration of their definition.

On this subject a fairly complete system of definitions is

[1] The club is indebted to Mr. P'tan Have, for assistance in the translation of this paper.

provided by the classical theory of elasticity. In applying the results of this theory in the field of rheology, however, it is important to distinguish between propositions which are true for deformations of any magnitude and those which are valid only in the limiting case of small deformations.

In this paragraph the point of view adopted is that which has been expounded in Love's *Mathematical Theory of Elasticity.* Some of the more detailed mathematical expositions are given in the Appendix.

Before defining stress, it is necessary to consider traction.

Traction

Traction is defined as the force per unit area acting across a specified plane within a body or at the surface of a body. The components of this force respectively perpendicular and parallel to the plane considered are termed the *normal* and *tangential* tractions.

Stress

Stress. The complete specification of the stress at a point *O* within a body involves a knowledge of the traction across all planes passing through *O*. In particular, if the tractions across a set of three mutually perpendicular planes through *O* are given, then the tractions across any other plane may be calculated. The tractions on the three mutually perpendicular planes, resolved into normal and tangential components, yield the six *components of stress* with respect to a given coordinate system.

Notes

(1) Traction is a *vector* quantity. Stress, being related to six vector components as defined above is a *tensor* quantity.

(2) Some authors (e.g., Morley, *Strength of Materials*, and Southwell, *Theory of Elasticity*) use the term stress in the sense of both traction and stress as defined by Love. Thus, if a bar is loaded in simple tension, the load per unit area of cross section is referred to as the "stress." This ambiguous usage is a source of confusion, and should be avoided.

(3) The stress at all points of a body at rest or in unaccelerated motion is determined solely by the applied forces. It is not, therefore, a function of the material.

Shear stress is of particular importance in rheology. It is defined as a system of two equal tangential tractions acting on planes at right angles to one another. In these planes there is no normal traction.

Note that the importance of distinguishing between stress and traction is here apparent. In planes other than those on which the normal traction vanishes there will be both normal and tangential tractions, varying in magnitude with the direction of the plane; and determined in magnitude by the direction and magnitude of the shear stress.

Strain

Strain. The concept of strain involves a comparison between two states, (*a*) the undeformed, and (*b*) the deformed. In a homogeneous strain (i.e., one which is the same at all points of a body) a sphere is transformed in general to an ellipsoid with three unequal axes. This is known as the *strain ellipsoid.* Conversely, it is possible to find a particular ellipsoid in the unstrained body which is transformed on deformation into a sphere. The original ellipsoid is called the *reciprocal strain ellipsoid.*

The general homogeneous strain may be defined in terms of the principal axes of either the strain ellipsoid or the reciprocal strain ellipsoid.

Strain, like stress, is a tensor quantity, and may be represented in terms of six components. (See appendix.)

Simple shear

Simple shear is a type of strain in which every point of a body is displaced parallel to a given line by an amount proportional to its distance from a fixed plane containing that line. The magnitude of the shear is the ratio of the displacement of a point to its distance from the fixed plane.

Notes

(1) In a *small* shear strain the principal axes of the strain ellipsoid make an angle of 45° with the direction of sliding. In a large shear this is no longer true.

(2) *The unstrained state.* Whilst mathematically any state has an equal claim to be regarded as the unstrained state, there may be physical reasons for preferring a particular state to represent the state of zero strain. An ideally elastic rubber, for example, is isotropic in one and only one state, and it is naturally simplest to consider this to be the unstrained state. A Newtonian fluid, on the other hand, is isotropic after any deformation, and there is no reason for choosing any particular state in preference to another as unstrained state.

(3) *The magnitude of "strain."* The general strain requires six numbers for its specification. In special cases, however, the strain may be represented by fewer than six numbers. In these simpler cases the classical components of strain may not be the most appropriate for the specification of the amount of strain. Shear strain, for example, may be represented by a single parameter, the amount of shear.

The type of strain undergone by a bar in simple tension cannot, in general, be represented by a single number, but requires the specification of at least two parameters (length and thickness). If, however, we are concerned only with the change in length, we may call this, for our immediate purpose, the "strain," which may be measured or defined in a number of ways, *viz.*

(i) *Engineering strain.* Defined as $(l-l_0)/l_0$. This is the simplest measure to adopt when the strain is small. It is also frequently used in an empirical manner when the strain is large.

(ii) *Natural strain* (Hencky). Defined as $\ln(l/l_0)$ or dl/l_0. This is likely to be useful in the case of a material which remains unchanged in its properties during deformation.

(iii) *Extension ratio,* or l/l_0. This is particularly useful in large elastic deformation, on account of its direct connection with the strain ellipsoid.

(d) *Elastic Moduli and their Reciprocals*

The three principal moduli are:

(i) For simple tension (length l increased to $l+\delta l$)

$$\text{Young's Modulus} = \frac{\text{Normal traction}}{\pm l/l_0}$$

(ii) For simple shear (line normal to plane of slide rotated through angle ϕ).

$$\text{Rigidity Modulus} = \frac{\text{Tangential traction}}{\tan\phi}$$

Reciprocal, Shear Coefficient.

(iii) For hydrostatic compression (volume V reduced by $\pm V$).

Modulus of Compression (or Bulk Modulus)

$$= \frac{\text{Hydrostatic pressure}}{\pm V/V}$$

Reciprocal, Coefficient of Compressibility.

(iv) In addition, we have in the case of simple tension,

$$\text{Poisson's ratio} = \frac{\text{Relative lateral contraction}}{\text{Relative longitudinal extension}}$$

Notes

(1) The definition of Rigidity Modulus is valid fo larger strains. The remaining three quantities above are not defined for large strains.

(2) The use of the terms "tangent" and "secant" moduli, ($dS/d\sigma$ and S/σ) by Lazan and Yorgiadis may be convenient in some cases. "Elastic compliance" (Alfrey) for shear coefficient, has the disadvantage that the type of strains is not indicated in the term. There is nothing to be said, however, for the common usage in rubber technology of the expression "modulus at (say) 300 percent extension, when what is meant is "force per unit area of the unstrained material at 300 percent extension."

4. VISCOSITY

Viscosities range from about 10 for liquid helium to about 10 for glass at 500°C, with many common liquids such as water (10) and golden syrup (10^2) occupying positions near the middle of the range. In hydrodynamics the viscosity of a liquid, even though numerically small, may be of great significance in determining the type of flow, namely, whether it is streamlined or turbulent. This influence is recognized in the so-called Reynolds Number, involving viscosity, which in a certain sense measures the hydrodynamical scale of any given field of motion.

(a) Newtonian Liquids

Newton, who attributed viscosity in fluids to "defectus lubricitantis" or internal friction, "attritus," clearly defined viscosity in terms of the tangential traction S and the velocity gradient du/dx in a simple shear. His equation is

$$S = \eta du/dx.$$

The unit of viscosity, η, is then that viscosity which corresponds to unit stress when the velocity gradient is unity, and is called the *Poise.* Its reciprocal, the unit of fluidity, is known as the *Rhe* (Bingham).

From Newton's equation, viscosity (η) has dimensions ML^1T^1.

Relaxation and orientation times

Poisson and Maxwell compared a liquid with an elastic solid in which the elastic reaction is continuously dissipated. If λ is the time taken for an instantaneously applied stress to fall to $1/e$ of its initial value (under constant strain), and n is the rigidity modulus, then the following relation may be shown to hold:

$$\eta = n \times \lambda$$

or viscosity $-$ rigidity $\times$ time of relaxation.

The Maxwell model of a liquid, and the time of relaxation defined thereby, provides a natural interpretation of the viscosity of liquids when these are approached from the solid state. If, on the other hand, we approach the liquid state from the basis of the gaseous state, we are led to regard viscosity as a diffusion process arising from the transfer of momentum between molecules in different parts of the flowing liquid.

Maxwell's model is mathematically equivalent to a spring and dashpot in series. In an alternative system, comprising a spring and dashpot in parallel, the application of a stress causes an asymptotic approach to a final limiting deformation. The deformation then follows the law

$$\sigma = A(1 - e^{t/\mu}).$$

This model is identical with Reiner's Kelvin solid (Section 2) and is appropriate as a first approximation to a certain class of non-ideal elastic deformations, as exemplified by high-molecular systems. The constant μ in the above equation has been called the "orientation time."

(b) Non-Newtonian Liquids

Many liquids do not follow Newton's simple law of flow. In such cases it is necessary to consider whether the rate of shear is determined solely by the shear stress, or whether time effects are present.

If the rate of shear is determined solely by the shear stress, a unique relation exists between stress and rate of shear. This relation completely defines the properties of the material. Suggested equations for such materials contain two or more constants, to which special names have been given. We do not propose to follow up these suggestions in detail, but will restrict ourselves to the general comment that where such non-linear equations are employed the symbol η and the term viscosity should not be used to indentify the constants. (It is considered permissible, however, to make use of the term "apparent viscosity" when referring to the reading of a particular instrument, or in a similar empirical sense, provided that it is made clear that the term is not used in the absolute sense of Newton's equation.)

(c) Structural Viscosity

Structural viscosity (or structure viscosity) is a special case of non-Newtonian viscosity in which the rate of flow is determined only by the shear stress, but in which the apparent viscosity $S/(d\ddagger/dt)$ falls with increasing stress. The term is not a good one, since it implies a theoretical breakdown of structure, but it is probably too well established to be discontinued.

(d) Kinematic Viscosity

In cases of varying motion we are often concerned not so much with viscosity itself as with the ratio of viscosity to the density or inertia of the fluid. The quantity η/d or η/i is known as the kinematic viscosity, and is measured in Stokes. Kinematic viscosity has the dimensions of a diffusion coefficient, i.e., $ML^{-1}T^{-1}/ML^{-3} = L^2T^{-1}$.

In industrial processes the rate of flow of liquids such as petroleum may be sufficiently high to be in the region where turbulence occurs, and for purposes of calculation the kinematic viscosity becomes important.

The Committee feel that the term "kinematic viscosity" should be retained, without, however, eliminating the term "viscosity" (as had been suggested by some authors).

(e) Specific and Intrinsic Viscosity

The term "specific viscosity" has frequently been used in connection with solutions. It is defined by the equation

$$\eta sp = (\eta - \eta_0)/\eta_0$$

where η and η_0 are the viscosities of solution and solvent respectively. Specific viscosity is a pure number.

"Intrinsic viscosity" is defined as

$$\eta = \lim_{c \to o} (\eta sp/c)$$

where c is the concentration. An equivalent definition is

$$[\eta] = \left(\frac{d\eta_{sp}}{dc}\right)_{c \to o}$$

The concentration c is variously expressed as (*a*) g per liter, (*b*) g per 100 cc, or (*c*) g per g.

Note

There is some opposition to the use of terms involving the word viscosity for quantities whose dimensions are not those of viscosity. If "intrinsic viscosity" is to be used, it is strongly recommended that c be measured in g per g.

5. REVERSIBLE AND IRREVERSIBLE CHANGES IN CONSISTENCY

Under this heading will be considered a number of more complex rheological phenomena in which the deformation is accompanied by a change in the state or properties of a material.

(a) Thixotropy

The clearest example of thixotropic behavior is that of a substance which changes from a state in which it is able to resist shearing stresses (below a yield value) to one in which it is unable to withstand shearing stresses as a result of the application of a shear, but which on resting gradually and completely returns to its original state. The term *thixotropic* is also applied by some authors to describe any material which suffers a loss of consistency on shearing, and which gradually reverts wholly or partially to its initial state on removal of the shear stress. Other workers have applied the term "false body" to this second type of behavior. Unfortunately *false body* is also used in quite a different sense in the paint industry, and the distinction between the two terms (thixotropy and false body) is by no means always clear.

Since it seems to us that the vanishing of a yield value is only a special case of reduction of consistency, we suggest that the term *thixotropy* be used to cover all such types of behavior, and that the term *false body* be avoided. The proposed definition of thixotropy is given below:

> *Thixotropy* is a reversible time-dependent loss of consistency accompanying the application of a shear, or the increase in the amount of the applied shear.

Notes

(i) The change of consistency may be related to the magnitude of the stress, or to the magnitude of the strain. These classes may be distinguished by the terms *stress-thixotropy* and *strain-thixotropy*.

(ii) The difference between structural viscosity and thixotropy lies in the absence of an observable time-lag in the former case.

(b) Work-Hardening and Work-Softening

Work-hardening is a commonly used term implying a nonreversible increase of consistency on shearing. Strain-hardening is sometimes used synonymously with work-hardening, but it seems desirable to distinguish the possibility of either the amount of strain or the amount of stress being the determining factor. We suggest, therefore, the use of *strain-hardening* and *stress-hardening*, with *work-hardening* as a general term including both types. *Stress-softening*, *strain-softening*, and *work-softening* may be used in corresponding senses when the consistency is irreversibly reduced on shearing.

The term "rheodestruction" has been suggested to indicate a non-reversible loss of consistency on shearing. This term is etymologically unfortunate, and is not favored by the Committee. "Shear breakdown" has been used in industry, e.g., to describe the loss in viscosity of polymer thickened fluids with use in aircraft.

(c) Rheopexy

The term *rheopexy* has been applied to the phenomenon exhibited by certain thixotropic systems (e.g., V_2O_5 sols) in which the rate of resetting is accelerated by slowly rotating the containing vessel.

(d) Dilatancy

The term *dilatancy* originally implied the expansion into an open packing which a system of closely packed spheres must necessarily undergo when stressed, before flow can take place. This rearrangement usually involves an increasing resistance to shearing, and in the simplest case the amount of "hardening" would be a function of the amount of strain. Following Williamson and Heckert's finding that for cornflour at least, the concentrations at which the phenomena occur do not correspond to close-packing, a problem in nomenclature arose. Should these phenomena be included under the term "dilatancy" irrespective of mechanism, or should some other term (e.g., "inverted plasticity" or "pseudo-dilatancy") be introduced?

Since it seems dangerous to speak of dilatancy in systems which do not dilate, and since in some cases, the extent of hardening may be a function of stress rather than of strain, it would seem preferable to speak of strain-hardening or stress-hardening in such cases, without reference to mechanism. Phenomenologically, dilatancy is a special case of strain-hardening, and the former term should be reserved for cases where a change of packing is proved.

6. "SPINNBARKEIT"

Many materials, such as white of egg and adhesive like seccotine, can be readily drawn into threads. In some cases these threads can be hardened to give fibers which can be spun, but in many instances this is not so. Erbring, who has worked extensively on this property uses the term "Spinnbarkeit" for the phenomenon, and his term is now in fairly common use among British Rheologists (e.g., Pryce-Jones, Clift). The term is clearly not sufficiently wide even in the original German, and is quite unsuitable in English. Attempts at literal translation (spinnability, fibrosity, etc.) are equally unsatisfactory.

There would seem to be a good case for an international word of classical origin. The first proposal (Pirie) of "leptogenesis" appears to mean "producing thinness," and the later alternative (McClean) "nematagenesis" would be preferable but for the circumstance that Bernal has adopted this term in the sense of "producing the nematic condition." It appears that the term "nematapoeic" has been introduced by McClean, and other possibilities which have been discussed are "mitogenic" and "closmagenic." These last three all seem to mean "thread producing," in the sense of a thread of cotton, which is not perfect but seems to be the best we can do at present. Investigations on this question are continuing.

APPENDIX—THE COMPONENTS OF STRAIN

The state of strain is completely determined when we know the lengths in the strained and unstrained states of corresponding lines. If ds_1 and ds are the lengths of corresponding linear elements in the two states, the relation between ds_1 and ds is a function of the direction cosines (l, m, n) of ds which may be expressed in the form

$$\left(\frac{ds_1}{ds}\right)^2=(1+2\epsilon_{xx})l^2+(1+2\epsilon_{yy})m^2+(1+2\epsilon_{zz})n^2 +2\epsilon_{yz}mn+2\epsilon_{zx}nl+2\epsilon_{xy}ln$$

where l, m, n are the direction cosines of ds. The components of strain $\epsilon_{xx}\cdots$, $\epsilon_{yz}\cdots$ are functions of the partial differentials of the components of displacement u, v, w of a point, i.e.

$$\epsilon_{xx}=\frac{\sigma u}{\sigma x}+\frac{1}{2}\left[\left(\frac{\sigma u}{\sigma x}\right)^2+\left(\frac{\sigma v}{\sigma x}\right)^2+\left(\frac{\sigma w}{\sigma x}\right)^2\right]$$
$$\epsilon_{yy}=\frac{\sigma v}{\sigma y}+\quad .\ .\ .\ .\ .\ .\ .\ .\ .$$
$$\epsilon_{zz}=\frac{\sigma w}{\sigma z}\quad .\ .\ .\ .\ .\ .\ .\ .\ .$$
$$\epsilon_{yz}=\frac{\sigma w}{\sigma y}+\frac{\sigma v}{\sigma z}+\frac{\sigma u}{\sigma y}\cdot\frac{\sigma u}{\sigma z}+\frac{\sigma v}{\sigma y}\cdot\frac{\sigma v}{\sigma z}+\frac{\sigma w}{\sigma y}\cdot\frac{\sigma w}{\sigma z}$$
$$\epsilon_{zx}=\frac{\sigma u}{\sigma z}+\quad .\ .\ .\ .\ .\ .\ .\ .$$
$$\epsilon_{xy}=\quad .\ .\ .\ .\ .\ .\ .\ .\ .\ .\ . \qquad (1)$$

strain, like stress, is a *tensor* quantity.

For any homogeneous strain it is possible to find an ellipsoid which becomes a sphere on deformation. This ellipsoid is called the *reciprocal strain ellipsoid*, and its axes the *principal axes of strain*. The quantity $ds/ds-1$ is called the extension of the linear element, and the extensions of the axes of the reciprocal strain ellipsoid are called the principal extensions.

Simple Shear

Defined by

$$x^1=x+\sigma y$$
$$y^1=y$$
$$z^1=z$$

The proportionality constant σ is the amount of the shear, and may be shown to be equal to difference of the two principal extensions in the plane (x, y). Moreover, the area of a figure in the (x, y) plane is unaltered by the shear strain.

Small Deformations

When the strain is small the squares and products of $\sigma u/\sigma x$, etc., in (1) vanish, and the components of strain take on a particularly simple form, i.e.

$$\epsilon_{xx}=\sigma u/\sigma x \qquad \epsilon_{yy}=\sigma v/\sigma y \qquad \epsilon_{zz}=\sigma w/\sigma z$$
$$\epsilon_{yz}=\frac{\sigma w}{\sigma y}+\frac{\sigma v}{\sigma z} \qquad \epsilon_{zx}=\frac{\sigma u}{\sigma z}+\frac{\sigma w}{\sigma x} \qquad \epsilon_{xy}=\frac{\sigma v}{\sigma x}+\frac{\sigma u}{\sigma y}.$$

BALLOT ON AMENDMENTS

Please return ballot to

Dr. R. B. Dow
Bureau of Ordnance, Re9d
Navy Department, Washington 25, D. C.

BEFORE AUGUST 15, 1947

The amendments to the Constitution and By-Laws of the Society of Rheology given in detail in this issue of the *Rheology Bulletin* should be accepted (see discussion on page 3).

Yes ☐ **No** ☐