# RHEOLOGY BULLETIN

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## THE SOCIETY OF RHEOLOGY EXECUTIVE COMMITTEE - 1999-2001



## COMMITTEES



## L. GARY LEAL 2000 BINGHAM MEDALIST

The Bingham medal of the Society for 2000 will be awarded at the Hilton Head meeting to Professor Gary Leal of of the University of California at Santa Barbara. A write-up appears inside this issue of the Bulletin.

## STUDENT POSTER COMPETITION

A $200 prize will be awarded to the best student poster at the Hilton Head meeeting. This is the first time that such a competition is being held. Details of rules are available on the meeting website.

## 72nd ANNUAL MEETING HILTON HEAD, SC FEBRUARY 11 - 15, 2001

The venue for the 72nd annual meeting is the Westin Resort on Hilton Head, SC. The meeting will start on Sunday evening, February 11 and end at noon on Thursday, February 15. The meeting organizers are:

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Information concerning meeting and hotel registration and transportation to Hilton Head may be found as an insert in this issue of the Bulletin.

## RHEOLOGY SHORT COURSE

A two-day short course entitled "Rheology of Colloidal Dispersions" will be offered in Hilton Head, February 10-11, 2001. The instructors are Professor Bill Russel of Princeton University and Professor Norm Wagner of the University of Delaware. A complete course description as well as registration information are given inside.

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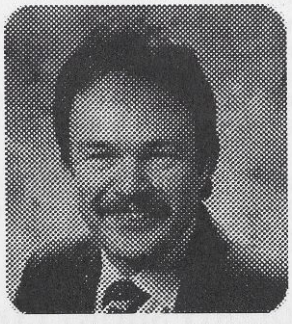
## 2000 BINGHAM MEDAL GOES TO L. GARY LEAL

Gary Leal, who is Professor of Chemical Engineering at the University of California at Santa Barbara, is being honored on account of his outstanding and wide-ranging accomplishments in rheology over the last thirty years and especially so during the past decade.

Gary was born in Bellingham, WA and received his B.S. in Chemical Engineering from the University of Washington in Seattle. After obtaining a Ph.D. at Stanford, he went to Cambridge University for post-doctoral training and then joined the faculty at Caltech from where he moved to U.C. Santa Barbara eleven years ago as Chairman of Chemical Engineering. The pre-eminence of that department as one of the Centers of Chemical Engineering on an International scale is a fitting testimonial to Gary's leadership and vision.

Gary has received numerous awards which include, to name but a few: election to the U.S. Academy of Engineering, a Guggenheim fellowship and the Colburn and Walker awards from the American Institute of Chemical Engineers. In addition, he is currently the co-editor of the Physics of Fluids, one of the two most prestigious journals in fluid mechanics.



Professor Gary Leal

Gary's research contributions to rheology cover an amazing spectrum of subjects and entail an almost perfect blend of analysis, computations and sophisticated experiments. For example, his research on drop deformation and breakup has brought results that are certain to become classic contributions. His experiments using the four roll mill produced the most complete set of measurements on this problem and may never be matched in thoroughness and precision. In fact, it is fair to say that Gary's results on the dynamics of droplets have laid the foundations for much of the present work on the rheology of blends and emulsions. Furthermore, Gary developed a general theory for describing the dynamics of orientable particles which has become the basis for subsequent constitutive theories for a wide range of microstructural materials. He was also among the first to recognize that the stretching of polymer chains in an inhomogeneous flow depends strongly on the residence time of the chain in different regions of the flow and by means of his ingenious use of optical rheometry obtained some of the most conclusive results on the subject. In addition, he popularized the concept of reptation with segmental stretch in entangled solutions and developed a vector-based version of the reptation model which retains the basic physics and is yet simple enough to allow calculations of nontrivial flows. He has authored over 200 papers plus one textbook and has been the Ph.D. thesis advisor of over 40 students.

Clearly, a more outstanding record would be difficult to imagine.

**Andreas Acrivos**

## COMMENTS FROM THE PRESIDENT GERRY FULLER

Over the past several years, the Society has undertaken a major review of its constitution. This was initiated by Past President Ronald Larson, and the efforts were coordinated by an ad hoc committee chaired by Faith Morrison. This process culminated in a vote on a series of proposed changes late last year, and I am writing to report on the outcome. The ballot consisted of seven issues, and the membership approved all of them by comfortable majorities. Overall, 500 members cast ballots in this important vote.

The proposal to change the qualifications for the Bingham Medal to include members of the Society residing outside of North America elicited the greatest debate. Nonetheless, 79% of the ballots were in favor of this important change. The call for nominations for the Bingham Medal contained in this Bulletin is the first to include this expansion in eligibility. Also connected with the Bingham Medal was the second issue, which proposed allowing the Executive Committee to set the monetary award (subject to the constraint that it not be changed more than twice in a five-year period). This measure won 86% of the vote.

The next election of officers in the year 2001 will see the addition of a third Member-at-Large on the ballot. This measure, which passed with 77% of the vote, will expand the representation of the Executive Committee and will offer increased opportunities for members to serve the Society and to become trained in its governance.

The remaining four issues that were presented for vote were motivated by a desire to improve the language of the constitution and to remove inconsistencies. They also involved legalistic clarification, adoption of gender-neutral language and correction of grammar and punctuation. These matters were all accepted with a strong majority of the votes cast.

The Society was certainly well served by the very careful

work by Faith Morrison and her committee. Successfully putting this ballot before the membership represented a tremendous amount of work, and I thank Faith on behalf of the Society. I am also pleased to announce that Faith has accepted the assignment to serve as Chair of the Membership Committee following the fine work by the previous Chair, Bill Vanarsdle.

## MINUTES OF THE EXECUTIVE COMMITTEE MEETING
### April 2, 2000

The meeting was called to order at 9 a.m. in the Red Carpet Lounge near Gate C16 of Terminal 1 of the Chicago O'Hare airport. Committee Members in attendance were Gerry Fuller, Susan Muller, Ron Larson, Monty Shaw, Morton Denn, Lisa Mondy, Jeffrey Giacomin and Bill Russel. Invited guests were Janis Bennett, Rakesh Gupta, Don Baird and Faith Morrison.

Susan Muller reported on the surplus of $4,005 resulting from Gerry Fuller's short course given at the University of Wisconsin during the October 1999 meeting.

Susan Muller led a discussion of the logistics of the inaugural Student Poster Presentation Award competition to take place at the Hilton Head meeting. It was decided that (1) the competition is open to all students, not only student members, (2) students could submit either a 2-page extended abstract of their poster, or a PowerPoint preprint in advance of the poster session, (3) eight finalists will then be selected from which (4) the winner, to be determined during the poster session by a panel of judges, will be awarded a $200 prize.

Susan Muller reported on the Education Committee. Bill Russel and Norm Wagner will teach a short course on Colloidal Systems on the weekend before the meeting in Hilton Head, South Carolina (February 10-11, 2001). The Executive Committee is soliciting proposals for short courses at future meetings, especially for the weekend before the Bethesda meeting (October 20-21, 2001).

Janis Bennett of the AIP distributed a list of 18 institutions that have yet to renew their institutional subscriptions.

Faith Morrison, the new Chair of the Membership Committee, reported on the plan for augmenting membership, especially outreach to new industrial members.

Faith Morrison reported on the Constitutional Reform Committee. The affirmative vote percentages (in parentheses) for the Constitutional Votes on each issue follow:

(1) Amendment to expand eligibility for the Bingham Medal to include residents of North America or any member of The Society of Rheology. (79%)
(2) Allow the Executive Committee to determine the monetary value of the Bingham Award. (86%)
(3) Amendment to add a third Member-at-Large to the Executive Committee. (77%)
(4) Minor substantive changes. (98%).
(5) Minor legalistic changes. (97%)
(6) Gender-neutral language. (93%)
(7) Grammar and punctuation changes. (98%)

The Secretary formally certified these results, and hereby certifies these to the members. These are based on the 498 cast ballots received by AIP. Regarding Item (3), it was decided that the Executive Committee would not expand until the next regularly scheduled Society election. Having completed its mission, the Constitutional Reform Committee was dissolved.

The Executive Committee passed a motion to double the Bingham medal award from $2,500 to $5,000. (effective after the Hilton Head meeting).

Don Baird reported on local arrangements for the meeting in Hilton Head, South Carolina (February 11-15, 2001). The cut-off date for preferred room rates at *The Westin Resort* is January 22, 2001, but earlier room registration is well advised.

For Local Arrangements Chair Carl Shultheisz, Gerry Fuller reported on the meeting in Bethesda, Maryland (October 21-25, 2001). The meeting will be held at the *Hyatt Regency Bethesda*.

For the Local Arrangements Chair Chris Macosko, Monty shaw reported on the meeting in Minneapolis, Minnesota (October 13-17, 2002). The meeting will be held at the *Radisson Hotel Metrodome*.

Gerry Fuller led a discussion on other future meetings. The Executive Committee is soliciting proposals for meetings in October 2003, February 2005 and October 2005.

A motion was passed to make student travel grants available to student members of the Society for attending the *International Congress on Rheology* in Cambridge (August 20-25, 2000). Details will be available at www.rheology.org.

Rakesh Gupta, *Rheology Bulletin* editor, gave a status report. New articles and advertiser are being solicited.

Treasurer Monty Shaw submitted a *Statement of Revenues and Expenses* on The Society of Rheology and on the *Journal of Rheology*.

Janis Bennett led a discussion on the future of electronic submission of journal articles.

Gerry Fuller led discussion on (1) including the back-issues of the journal into the *Journal of Rheology Online*, (2) revising membership dues, (3) creating a separate price for membership excluding journal subscription.

A motion was passed to raise the institutional journal rate by $75 and to put the back-issues of the *Journal of Rheology* onto the *Journal of Rheology Online* according to the recent AIP proposal authored by Frank Perugini.

A motion was passed for The Society of Rheology to contribute to the 2000 Physics Olympiad.

Fuller reported that Sangtae Kim has agreed to represent The Society of Rheology on the United States National Committee on Theoretical and Applied Mechanics.

Following a brief executive session, the meeting was adjourned at 4:30 p.m.

### Nominations for the 2001 Bingham Medal

Nominations are invited for the 2001 Bingham award. These should be submitted before January 12, 2001 to the next chair of the Bingham Award Committee, Professor Bamin Khomami, at Department of Chemical Engineering, Washington University, Campus Box 1198, St. Louis, MO 63130-4899. Professor Khomami's e-mail address is bam@poly1.che.wustl.edu. New award guidelines may be found at http://www.rheology.org/ Note that these guidelines now permit the nomination of any member of the Society, regardless of the continent of residence.

## TECHNICAL PROGRAM FOR HILTON HEAD

Authors should submit an abstract after September 1, 2000, but before **October 27, 2000,** through the World Wide Web using the SoR abstract submission page at www.rheology.org. The planned symposia and the corresponding chairs are:

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### 2. NON-NEWTONIAN FLUID DYNAMICS AND FLOW STABILITY

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# DETERMINING MOLECULAR WEIGHT DISTRIBUTIONS FROM THE RHEOLOGICAL PROPERTIES OF POLYMER MELTS*

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The state-of-the art for determining molecular weight distributions from melt rheological properties is described. A summary of the different models is presented. The article then focuses on the so-called "Modulus Model" with emphasis on an evaluation of the recently commercialized software from Rheometric Scientific, Inc.

## Introduction

Although the recent literature abounds with examples of determining the MWD from rheological properties, many people still wonder why one would bother when SEC has been around for decades and is the classical technique for such determinations. One answer is that SEC requires dissolution of the sample and some polymers are difficult to dissolve, like the semicrystalline fluoropolymers made from tetrafluoroethylene [1-3]. However, even for polymers which can be dissolved reasonably easily, rheological measurements are capable of detecting subtle structural differences between samples that SEC is not capable of, such as long chain branching (LCB) [4]. However, SEC and rheology are not competing techniques. Quite the contrary, they complement each other nicely, for example, in determining the probable presence of LCB. Both techniques therefore work together in defining structures needed to get desired rheological behavior and leading to more precise characterization for patent protection.

## Methods of Determining MWD from Rheology

Two general models have been used for MWD determinations: the "Viscosity Model" and the "Modulus Model". The first workable method of determining MWD from the Viscosity Model [5,6] was based on the work of Bersted and Slee [7] as well as Malkin and Teishev [8]. The model is derived from some simple assumptions relating molecular structure to the viscosity flow curve. First, the zero shear viscosity of a polydisperse mixture is assumed to be proportional to the 3.4 power of the weight average molecular weight:

$$\eta_{o,mix} = K_1(\overline{M}_W)^{3.4} \quad (1)$$

Next, the deformation rate, r, axis is transformed to molecular weight using the following relation:

$$\frac{1}{r} = K_2(M)^{3.4} \quad (2)$$

where r can be either the shear rate in a steady shear flow experiment or the frequency in oscillatory flow. Finally, a very simplistic flow curve is assumed for each monodisperse component. The double logarithmic plot of the flow curve is assumed to be constant below a critical deformation rate $r_c$ and above this rate has a slope of "-1" as depicted in Eqs. 3 and 4.

$$\eta(\dot{\gamma}) \text{ or } \eta^*(\omega) = \text{constant} \quad [r < r_c] \quad (3)$$

$$\eta(\dot{\gamma}) \text{ or } \eta^*(\omega) = K_3 r^{-1} \quad [r > r_c] \quad (4)$$

In this paper, however, we will be stressing the Modulus Model because it is far more sensitive to low concentrations of high MW components which usually dominate melt processability. The latter is especially true when extensional flows are involved [9]. A generalized form of this model is represented in Eq. 5, as presented by Meier, et al. [10] in terms of the relaxation modulus G(t).

$$\frac{G(t)}{G_N^0} = \left( \int_{\ln(M_e)}^{\infty} F^{1/\beta} F(t,M) w(M) d(\ln M) \right)^{\beta} \quad (5)$$

In Eq. 5, G(t) is normalized by the plateau modulus $G^0_N$. F(t,M) is a kernel function describing the relaxation behavior of a monodisperse component of molecular weight M, where the time is related to M by:

$$t = K_4(M)^{3.4} \quad (6)$$

where w(M) is the weight fraction MWD function. The exponent beta is a parameter which characterizes the mixing behavior of the chains. For example, beta is 1 for simple reptation and 2 for double reptation theory. $M_e$ is the entanglement MW.

The following "conventional" kernel functions, F(t,M), have typically been used [10,11]:

*Presented at the Society of Rheology Meeting, October, 1999

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*The Step-Function* is the simplest function. It assumes that the monodisperse component with M molecular weight will relax instantly at a time t as described in Eqs. 7. Although this is a somewhat unrealistic description

$$F_1(t,M) = 1 \text{ if } t < \tau_o(M) \tag{7a}$$

$$F_1(t,M) = 0 \text{ for all other } t \tag{7b}$$

of relaxation behavior, its simplicity enables one to determine the MWD without resorting to complex mathematical procedures like regularization.

*The Single Exponential* is the simplest relaxation function approximating the relaxation behavior in a qualitatively realistic way.

$$F_2(t,M) = \exp[-t/\tau_o(M)] \tag{8}$$

*The Doi Kernel* is a summation of single exponentials which describes a more gradual and more quantitatively realistic relaxation.

$$F_3(t,M) = \frac{8}{\pi^2} \sum_{n \in odd}^{\infty} \frac{\exp\left[-tn^2/\tau_o(M)\right]}{n^2} \tag{9}$$

*The BSW Kernel*

$$F_4(t,M) = \alpha \int_0^1 u^{\alpha-1} \exp[-t/\tau_o(M)u] \tag{10}$$

where $$\alpha = \sqrt{\frac{J_e^o G_N^o}{J_e^o G_N^o - 1}} - 1$$

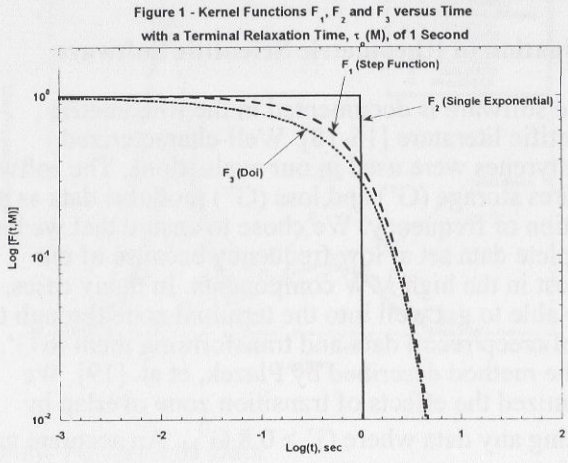
*The des Cloizeaux Kernel*

$$F_5 = \left( \frac{8}{\pi^2} \sum_{n \in odd}^{\infty} \frac{1}{n^2} \exp\left\{ -n^2 \left[ \frac{t}{\tau_o(M)} + \frac{M}{12.5 M_e} g\left( \frac{tM}{12.5 M_e \tau_o(M)} \right) \right] \right\} \right)^2 \tag{11}$$

where $$g(x) = \sum_{m=0}^{\infty} \frac{1 - \exp(-m^2 x)}{m^2}$$

and $J^0_e$ is the steady state compliance.

The BSW and des Cloiseaux kernels are even more mathematically sophisticated than the Doi kernel and have even more flexibility in describing relaxation behavior. Figure 1 represents $F_1$, $F_2$ and $F_3$ graphically. Functions $F_4$ and $F_5$ would be similar to $F_3$.




Some precautions are in order when dealing with these models. First, and very importantly, they apply only to polymers with no LCB. Other assumptions are that we are dealing with a polymer that: is unblended with either fillers or another polymer; has no ionic interactions; is completely melted with no remnants of crystallinity remaining. In short, we must deal with a polymer melt in which the entanglements overwhelmingly dominate the relaxation. Also, only very small amounts of oligomer less than the critical MW (Mc) can be present. Substantial amounts of low MW material will dilute the polymer and give a falsely low reading in MW. Finally, we assume that we are dealing with random coil chains (i.e. not liquid crystalline systems).

**An Historical Comparison of Modulus Models**

Wu [12,13] was one of the first to attempt MWD calculations from rheological data. He assumed that single reptation and single exponential behavior governed the relaxation. Thus, beta = 1 and $F_2$, the Single Exponential kernel, were used in Eq. 5. This led to an adequate representation of nearly monodisperse samples but very poor representation of bimodal blends.

Tuminello [14] assumed double reptation and the oversimplifying Step Function behavior for the kernel. Although these assumptions predicted a falsely broad distribution for nearly monodisperse melts, the predictions were reasonably accurate for bimodal blends and broad distribution polymers. A clear advantage in predicting the MWD of bimodal blends was illustrated in Fig. 20 of [14] versus using the simple reptation assumption of Wu.

Mead [15] improved the representation of nearly monodisperse, broad and bimodal distribution melts as illustrated in Fig. 7 of [15]. He used the double reptation assumption with a Single Exponential kernel. Mead's

approach was commercialized by Rheometric Scientific, and the remainder of this paper is devoted to its evaluation.

## Evaluation of Rheometric Scientific Software

The software is documented in the Rheometric Scientific literature [16-18]. Well-characterized polystyrenes were used in our evaluations. The software requires storage (G') and loss (G") modulus data as a function of frequency. We chose to ensure that we had a complete data set at low frequency because of our interest in the high MW components. In many cases, we were able to get well into the terminal zone through the use of creep/recoil data and transforming them to G', G" via the method described by Plazek, et al. [19]. We minimized the effects of transition zone overlap by deleting any data where $G' > 0.8\ G^0_N$. An accurate value of $G^0_N$ ($1.70 \times 10^5$ Pa) [14] needed for an accurate determination of the distribution breadth. The "Front Factor", $K_4$ defined in Eq. 6, had to be empirically determined, as a calibration step, for an accurate estimation of the MW averages. $K_4 = 4.52 \times 10^{-18}$ for the "Old Polystyrene Data" and $3.02 \times 10^{-18}$ for the "New Data". All data were shifted to 160 C prior to analysis.

The fitting of Eq. 5 to the G', G" data is the most crucial part of the operation. It requires good judgement to get reasonable information. Transparent to the user, the G', G" data are transformed to G(t), so that Eq. 5 can be used directly. As mentioned earlier, G', G" data from oscillatory flow and creep/recoil measurements were combined. The fit was accomplished by assuming a functional form to the MWD function w(M). The form could be either the Schulz-Flory or "Log Normal" distribution. One must also choose whether two terms (bimodal distribution) or one term (unimodal distribution) of the distribution functions are needed to describe the data. Empirically, one chooses the approach which minimizes the error. If the error was not reduced by using two terms of w(M), one term was chosen by default. The adjustable parameters in the fitting operation are $\overline{M}_w$ and $\overline{M}_w/\overline{M}_n$. One value of each parameter (4, in all) is needed for the bimodal distribution fit.

We first directly compare the Mead approach, using a Single Exponential kernel, with that of Tuminello, using the Step Function. The data to be evaluated in the "Old Polystyrene Data" section are described in more detail in [14]. These data have some faults and "New Polystyrene Data" were evaluated as well.

(1) Old Polystyrene Data

The data in Table I summarize comparison of the Rheometrics and Tuminello methods for determining the MWD of well-charaterized polystyrenes. The nearly monodisperse samples are designated by their peak MW. For example, 34K refers to a narrow distribution sample with peak MW of 34,000 Da. The SEC data were obtained using a refractive index detector. A broad distribution standard from NIST was also evaluated and designated as NBS706. It is currently known as SRM706. Three bimodal distribution blends were also analyzed and are designated by their nearly monodisperse components.

**Table I**

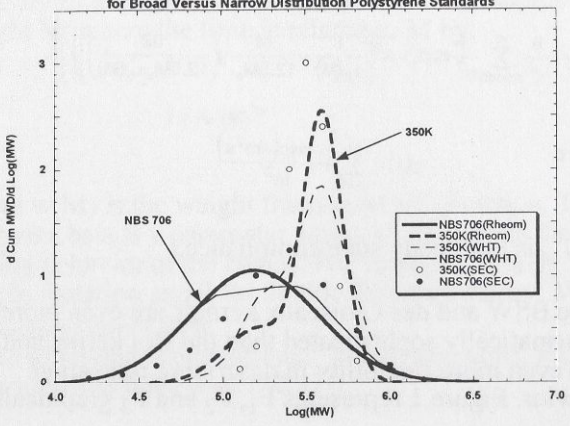
**Comparison of Weight Average MW and Polydispersity Ratio for Polystyrene by Rheometry (WHT & Rheom) and SEC**

| | $\overline{M}_W$(X10$^{-3}$) | | | $\overline{M}_W/\overline{M}_N$ | | |
|---|---|---|---|---|---|---|
| Sample | SEC[1] | WHT[1] | Rheom[2] | SEC[1] | WHT[1] | Rheom[2] |
| 34K | 32.4 | 32.9 | 30.3 | 1.06 | 1.26 | 1.10 |
| 68K | 66.4 | 67.7 | 67.1 | 1.04 | 1.23 | 1.09 |
| 115K | 124 | 120 | 123 | 1.03 | 1.30 | 1.16 |
| 350K | 346 | 333 | 347 | 1.13 | 1.37 | 1.38 |
| 675K | 627 | 646 | 682 | 1.20 | 1.54 | 1.60 |
| 1150K | 774 | 813 | 861 | 1.85 | 1.97 | 1.84 |
| NBS706 | 258 | 230 | 226 | 2.24 | 2.28 | 2.18 |
| 34+115K | 74.8 | 80.1 | 75.1 | 1.53 | 1.56 | 1.39 |
| 34+1150K | 435 | 462 | 395 | 6.37 | 5.83 | 4.72 |
| 115+1150K | 426 | 458 | 428 | 2.60 | 2.74 | 2.65 |

[1]W. H. Tuminello, Reference 14.
[2]Calculated from the Rheometric Scientific software.

The three lowest MW, narrow distribution standards are better characterized by the Rheometric software, whose predicted polydispersity ratios, $\overline{M}_w/\overline{M}_n$, are much closer to those determined by SEC. The higher narrow distribution samples all had a disturbing extra peak or shoulder at the low MW end of the distribution. This is shown for sample 350K in Figure 2. Figure 2 is a plot of selected differential MWD functions where the data points represent SEC results, the broad lines are the Rheometric determinations, and the narrow lines are those of the Tuminello/DuPont method. This peak or

**Figure 2 - MWD Determined from DuPont and Rheometrics Software plus SEC for Broad Versus Narrow Distribution Polystyrene Standards**

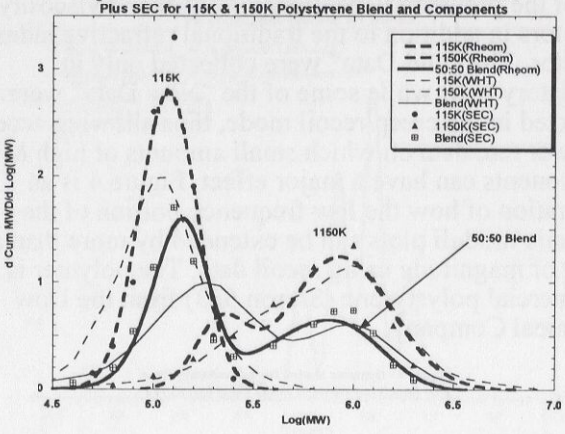


shoulder, on samples like 350K, is thought to be due to the overlap with the transition region and/or the lack of sensitivity of rheological measurements to the low MW side of the distribution. The Rheometric determination of the MWD, as illustrated in Figure 2, is closer to the shape determined by SEC for this narrow distribution sample.

The $\overline{M}_w$ of sample NBS706 was determined to be about 12% too low by both rheological techniques. As will be shown later, this appears to be caused by a sizable portion of polymer whose MW is lower than $M_c$. Figure 2 shows that the Rheometric method gives a more realistic shape to the distribution for NBS706 than the DuPont method.

Looking at the two blends with the 34K component in Table I, we see that the Rheometric predictions for the polydispersity ratio are quite low. This is probably due to the fact that the 34K sample is at the critical MW, $M_c$, and many of the model assumptions are inapplicable in this situation. This argument is strengthened when we look at the other blend whose low MW component has a MW of 115,000 Da. In this case, the predictions are well within the experimental error of the SEC data. The differential distributions of these blends are illustrated in Figure 3. In this figure, it is evident that the Mead model predictions for the narrow distribution sample and the bimodal blend are much closer to those predicted by SEC than the Tuminello/DuPont model which used the step-function kernel.

Figure 3 - MWD Determined from DuPont and Rheometrics Software Plus SEC for 115K & 1150K Polystyrene Blend and Components




(2) New Polystyrene Data

There were some deficiencies in the "Old Data" that we wished to correct to strengthen the evaluation procedure. The "Old Data" were collected on a Rheometrics System IV rheometer. The apparatus had a convection oven with which temperature control to less than 1 C was difficult to maintain. The new rheometer was a Bohlin controlled stress apparatus with electrically heated plates which allowed control to within 0.1 C with maximum gradients

of the same order. Better SEC data are now available by use of the previously mentioned MALS and viscosity detectors in addition to the traditional refractive index detector. The "Old Data" were collected only in oscillatory flow while some of the "New Data" were collected in the creep/recoil mode, thus allowing access to lower rate data on which small amounts of high MW components can have a major effect. Figure 4 is an illustration of how the low frequency portion of the dynamic moduli plots can be extended by more than an order of magnitude using recoil data. The polymer is a commercial polystyrene (Styron 663) from the Dow Chemical Company.

Figure 4 - Dynamic Moduli from Oscillatory Flow and Recoil Experiments at 190°C for Styron 663

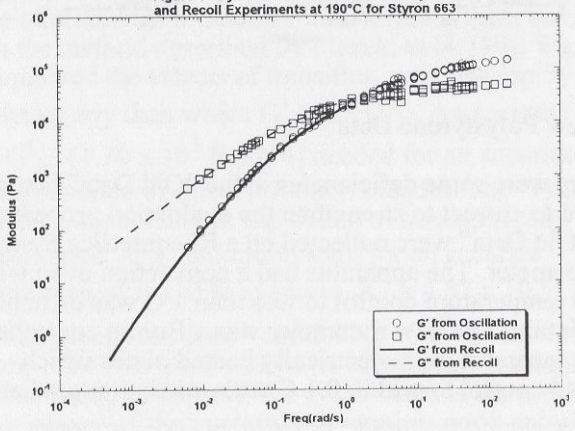



Table II and Figure 5 summarize the results of analyzing other polystyrenes which were characterized by SEC. The samples labeled 220K and 275K are nearly monodisperse samples from Polymer Laboratories. The numbers refer to the peak MWs as determined by Polymer Labs. Although the graphic representation of the distributions from SEC and rheometry does not show close agreement, the tabulated data show agreement within about 10%. In fact, the polydispersity ratios, $\overline{M}_W/\overline{M}_n$, agree well within 10% which is acceptable for SEC results between laboratories.

NBS706 was reanalyzed, both by SEC and rheometry. The results are shown in Table II plus Figures 6 and 7. It is obvious from Figure 6 that care and good judgement must be taken when interpreting data. Two different

**Table II**

**Comparison of Rheometric Determination of MWD with SEC**

| | SEC* | | | Rheometric | | |
|---|---|---|---|---|---|---|
| | $\overline{M}_Z$ | $\overline{M}_W$ | $\overline{M}_N$ | $\overline{M}_Z$ | $\overline{M}_W$ | $\overline{M}_N$ |
| 220K | 214000 | 206000 | 196000 | 234000 | 215000 | 196000 |
| 275K | 275000 | 258000 | 242000 | 297000 | 261000 | 225000 |
| Styron 663 | 443000 | 280000 | 142000 | 502000 | 275000 | 139000 |
| NBS 706 | 409000 | 265000 | 143000 | 358000 | 201000 | 84100 |

*Data of P. Cotts using MALS and RI detectors.

Figure 5 - Comparison of Differential MWD Determined from Rheometry and SEC

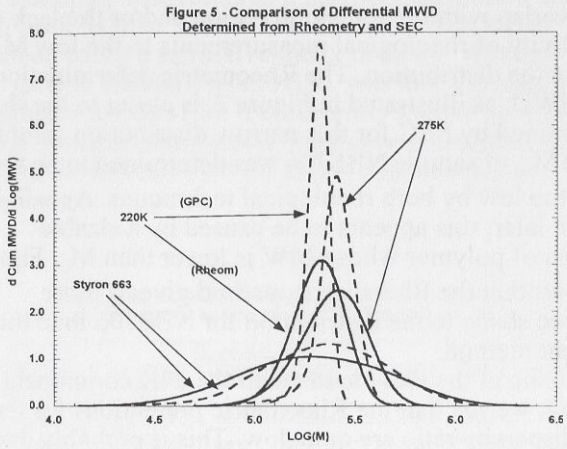



Figure 6 - Comparison of Schulz and Bimodal Fits for Dynamic Moduli of NBS706 at 160°C

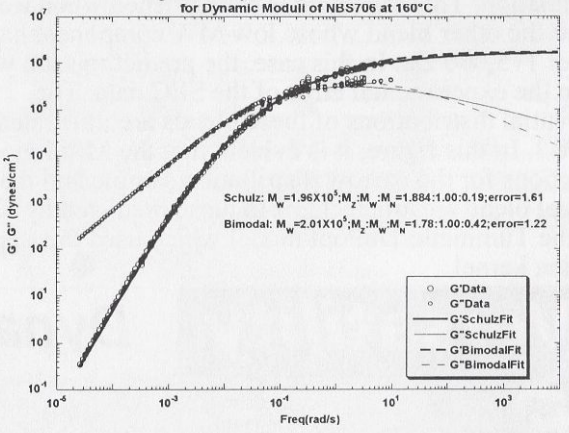
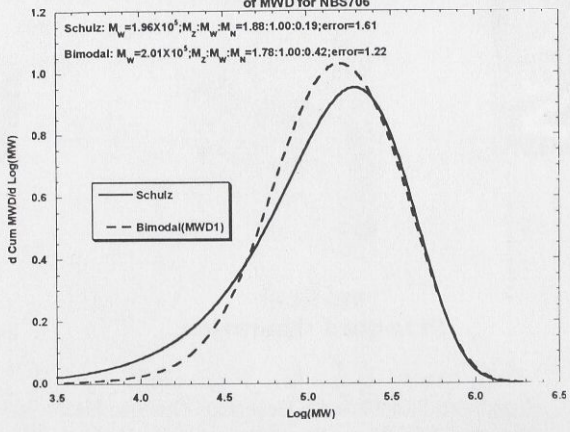



Figure 7 - Comparison of Schulz and Bimodal Rheometric Predictions of MWD for NBS706




fitting approaches give low errors, and the discrepancies in the fits occur at high frequencies where there are no

data. This leaves some ambiguity in terms of the low MW end of the distribution. The high MW end is very reproducible with little ambiguity, however, as shown in Figure 7. This is fortunate, since this end of the distribution has the greatest effect on polymer processability. Also, the MW averages are quite a bit lower for the Rheometric determination in comparison with SEC. This is consistent with the findings of Boni and Sliemers [20] that NBS706 has a sizable fraction of oligomeric component (<30,000 MW) which acts as a plasticizer.

To this point we have compared the rheological findings with those of SEC, assuming the latter is the standard by which comparisons should be made. However, there is some concern about the accuracy of SEC. To address this, Wasserman and Graessley [11] prepared two broad distribution polystyrenes from nearly monodisperse components by solution blending. The components of these two samples, $M_1$ and $M_2$, are listed in Table III. Assuming a "log normal" distribution for each component, the MWDs were constructed for each blend and are shown in Figure 8 with their calculated MW averages. The only difference between the samples is a slightly greater amount of high MW component for $M_2$.

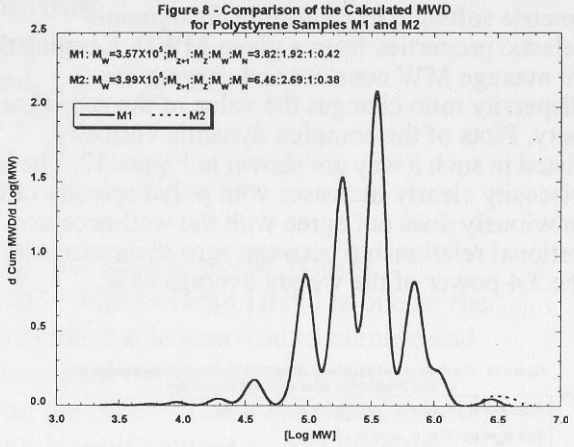
The dynamic moduli were determined from oscillatory flow and creep/recoil measurements in our laboratories. The results of the best fits to the data are shown in Figure 9. There is a dramatic difference in the storage moduli with such a small difference in MWD. The resulting MWDs from the fits shown in Figure 9 are illustrated in Figure 10. In Figure 11, the MWDs for sample M2 determined by SEC and rheology are compared with the calculated distribution. The SEC determination is quite close to that calculated, but the rheological determination lacks the resolution. The latter is probably due to the very high precision and accuracy required (may be unrealistically high) of the rheological data to get such resolution when the inverse operation of determining the MWD function from Eq. 5 is used.

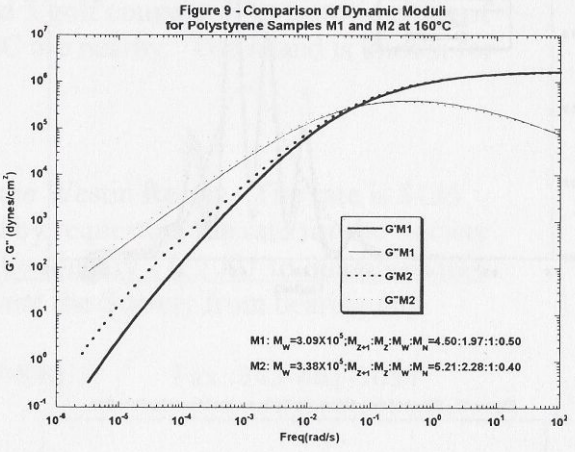
**Table III**

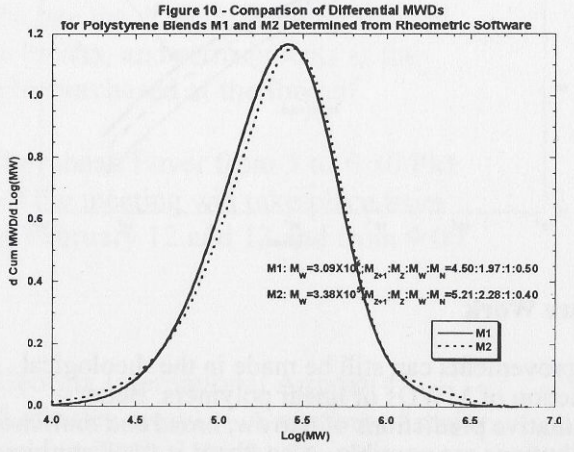
**Solution Blended Broad Distribution Polystyrenes***

| component | $M_i$ (X10$^{-5}$) ($M_p$, Tosoh) | M1** | M2** |
|---|---|---|---|
| 1 | 0.0298 | 0.001 | 0.001 |
| 2 | 0.0557 | 0.002 | 0.002 |
| 3 | 0.0910 | 0.004 | 0.004 |
| 4 | 0.1960 | 0.008 | 0.008 |
| 5 | 0.379 | 0.030 | 0.030 |
| 6 | 0.964 | 0.150 | 0.148 |
| 7 | 1.90 | 0.260 | 0.257 |
| 8 | 3.55 | 0.358 | 0.353 |
| 9 | 7.06 | 0.140 | 0.139 |
| 10 | 10.9 | 0.039 | 0.038 |
| 11 | 28.9 | 0.008 | 0.010 |
| 12 | 38.4 | --- | 0.007 |
| 13 | 44.8 | --- | 0.003 |

*Wasserman & Graessley[11] **weight fraction




Although, we generally support the use of the Mead approach in determining the MWD from rheological

data, there is a disturbing feature. One can use the Rheometric software to determine the dynamic viscoelastic properties from a given MWD. Keeping the weight average MW constant and varying the polydispersity ratio changes the value of the zero shear viscosity. Plots of the complex dynamic viscosity calculated in such a way are shown in Figure 12. The low rate viscosity clearly increases with polydispersity ratio. This obviously does not agree with the well-accepted proportional relationship between zero shear viscosity and the 3.4 power of the weight average MW.

Figure 11 - Comparison of the Calculated MWD for Polystyrene Sample M2 with Predictions from GPC and Rheometry

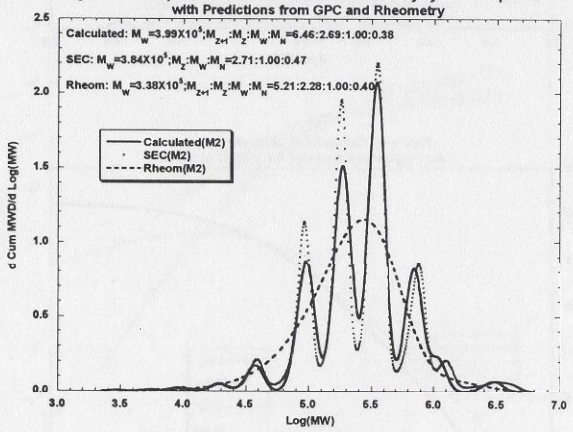
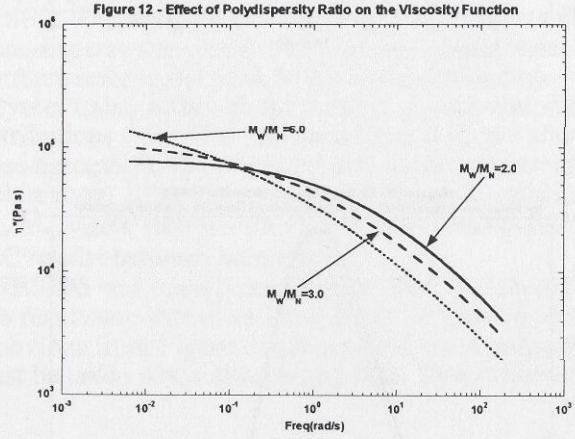



Figure 12 - Effect of Polydispersity Ratio on the Viscosity Function




## Future Work

Improvements can still be made in the rheological prediction of MWDs of linear polymers. Better quantitative predictions of narrow, broad and multimodal distributions are possible. Also, there is the disturbing prediction that the zero shear viscosity increases with polydispersity ratio using Mead's model. Maier, et al. [10] have used the unique approach of empirically optimizing the exponent beta in Eq. 5 to a value of 3.84. The physics behind this is not clear and more work appears necessary to evaluate the worth of this approach. Marin [21] has indicated that by emphasizing more strongly the interactions between long and short chains, that zero shear viscosity is not a function of polydispersity and can be accurately predicted using mixing rules he and his coworkers have developed.

Determining the MWD of polymers with LCB has thus far proven elusive although much recent progress has been made. The most prolific worker in developing constitutive equations to account for the effects of LCB has been McLeish, whose publications in this area are too numerous to list, but one of the most recent articles is referenced [22]. Kasehagen and Macosko [9] have also done interesting work in this area. A very important contribution has been made by Janzen and Colby [4]. They have developed a Cayley Tree model through which the average amount of LCB can be determined using only the zero shear viscosity and the weight average MW from SEC. With this recent progress, one is confident that the elusive problem of characterizing the MWD and LCB in polyethylene is not far from being solved.


## Acknowledgements

I gratefully acknowledge the careful, well thought out work of Dr. Patricia Cotts of the DuPont Company. She is one of my chief collaborators in this research supplying high quality SEC data using multi-angle light scattering, RI and viscosity detection. Mark Grehlinger (Rheometric) was invaluable for writing the MWD determination software and modifying it in a timely fashion. He is a pleasure to work with: prompt, cooperative and highly competent. Prof. Dave Mead (U. Michigan) was the main driving force for developing and commercializing the Rheometric technique for MWD determination.


## References


1. W.H. Tuminello, T.A. Treat, A.D. English, Macromolecules, **21**, 2606 (1988).
2. W.H. Tuminello, Polym. Eng. Sci., **29**, 645 (1989).
3. W.H. Tuminello, W.H. Buck, D.L. Kerbow, Macromolecules, **26**, 499 (1993).
4. J. Janzen, R.H. Colby, J. Mol. Structure, **485-486**, 569 (1999).
5. W.H. Tuminello, N. Cudre-Mauroux, Polym. Eng. Sci., **31**, 1496 (1991).
6. M.T. Shaw, W.H. Tuminello, Polym. Eng. Sci., **34**, 159 (1994).
7. B.H. Bersted, J.D. Slee, J. Appl. Polym. Sci., **21**, 2631 (1977).
8. A.Y. Malkin, A.E. Teishev, Polym. Eng. Sci., **31**, 1590 (1991).
9. L.J. Kasehagen, C.W. Macosko, J. Rheol., **42**, 1303 (1998).

# Meeting Information
## 72nd Annual Meeting
## Hilton Head Island, SC
## February 11-15, 2001

### Location

The 2000 Annual Meeting of the Society of Rheology will be held at the Westin Resort(Port Royal Plantation), Hilton Head Island, SC. Hilton Head Island is one of the most favored resort destinations in the world with a comfortable year-round climate and extraordinary recreational amenities. The island is bordered by 12 miles of white sandy beaches on one side and the intracoastal waterway on the other. There are riding stables, nature preserves, miles of jogging and bike paths, and 30 golf courses to choose from. The hotel is situated directly on the ocean and has many amenities including a fitness center, outdoor and indoor pools, tennis courts, and 3 golf courses. The historic cities of Savannah, Georgia, Buffort, SC, and Charleston, SC are nearby. The Island is known for its many fine restaurants.

### Hotel Registration

Hotel reservations are to be made directly with the Westin Resort. The rate is $135 per room per night plus taxes. This rate is obtained by requesting the rate for the Society of Rheology Meeting. Reservations must be made by January 11, 2001 to quarantee this rate as any rooms not taken will be released to prevent the Society from bearing any penalties.

Phone: 843-681-4000 or 800-937-8461 Fax: 843-861-1087

### Meeting Registration

The meeting registration form may be downloaded from the Society's web page at http://www.umche.maine.edu/sor/. The registration fee is $115 and may be paid by check or credit card(Master Card and Visa only) to "Society of Rheology-Annual Meeting". Payments received after January 18, 2001 will incur a late fee. The registration fee will include the abstract booklet, three receptions, coffee breaks, and refreshments at the poster session. Banquet tickets will be $45 and can be purchased at the time of registration.

Registration at the meeting will take place in the Savannah Foyer from 3 to 6:30 PM Sunday, February 11. Registration for the duration of the meeting will take place from 8:00 AM to 12:00 PM and from 2:00 to 4:00 PM on February 12 and 13 and from 9:00 AM to 12:00PM on Wednesday February 14.

### Transportation

Hilton Head is accessible from either Savannah, Georgia International Airport(45 minutes by car) or the Hilton Head Island Airport(5 minutes away). A number of major air carriers service Savannah while only commuters service Hilton Head. Shuttle service can be arranged through the Hotel.

# The Society of Rheology

**Presents**
**A Two-Day Short Course on**

## *Rheology of Colloidal Dispersions*

**by**

**William B. Russel**
**Princeton University**

**Norman J. Wagner**
**University of Delaware**

**Dates: Saturday & Sunday, February 10 & 11, 2001**. The short course is held in conjunction with the 72nd Annual Meeting of the Society of Rheology, February 11-15, 2001. The course will begin at 8:30 am on the Saturday.

**Location: The Westin Hotel and Conference Center on Hilton Head Island, South Carolina.**

## COURSE DESCRIPTION

This course will give an overview of dispersion rheology and how that rheology arises from colloidal level forces. It is appropriate for the practitioner seeking to control products and processes, as well as researchers interested in structure-property relationships in complex fluids. Only a basic knowledge of physical chemistry is a prerequisite.

The highly nonlinear and time-dependent rheology of colloidal dispersions derives from the coupling among interparticle and Brownian forces, hydrodynamic forces due to an imposed flow, and the non-equilibrium microstructure. Successful formulation and processing requires control of the rheology through the physical chemistry; conversely, the rheological response can be used to characterize colloids in situ. This course will be motivated by this coupling between microscopic and macroscopic behavior, seeking to convey the qualitative understanding needed to address current technological and scientific problems in dispersion rheology.

The introduction will review the relevant interparticle and hydrodynamic forces and the resulting stability, phase behavior, and dynamics. Then we will examine in detail the microscopic origin of stresses and the effect of shear on the microstructure. Then from dimensional analysis and simple models one can anticipate the sensitivity or insensitivity of different aspects of the rheology to colloidal forces and the development of structure-property relationships for dispersion rheology. This will also lead into a presentation of appropriate rheological measurements and rheo-optical and scattering techniques for detecting the non-equilibrium microstructure.

These underlying principles will be illustrated through the rheology of model dispersions:

- hard spheres and rods,

- charged and polymerically stabilized spheres,
- adhesive hard spheres,
- dispersions subject to depletion attractions, and
- dispersions containing associative polymer.

These relate the equilibrium phase behavior and the rheology qualitatively and, with existing theory, yield quantitative scalings for the dependence of the low shear viscosity; critical, yield, and Bingham stresses; and high frequency modulus on the particle volume fraction and the strength and range of the interparticle forces. Simple empirical models will be introduced where appropriate.

Special attention will also be devoted to

- shear thickening and dilatancy of concentrated dispersions,
- more complex dispersions such as clays or swollen microgels,
- computer simulations capable of predicting rheological response,
- optical techniques including rheo-optics, and
- means of characterizing the interparticle forces via rheological measurements.

## About the instructors:

**William B. Russel** is a Professor in the Department of Chemical Engineering and the Princeton Materials Institute. He is well known for his research on the phase behavior and rheology of colloidal dispersions and is co-author of *Colloidal Dispersions* published by Cambridge University Press. He is a member of the National Academy of Engineering and the American Academy of Arts and Sciences and received the Walker Award from the AIChE in 1992 and the Bingham Medal from The Society of Rheology in 1999.

**Norman J. Wagner**, a Professor of Chemical Engineering at the University of Delaware, has interests spanning colloid and polymer science. Within an extensive rheological and rheo-optical laboratory he addresses dispersions, liquid crystalline polymers, and dendrimers and hyperbranched polymers, producing rheological, optical, and neutron scattering methods for characterization, as well as fundamental understanding of phenomena such as dilatancy. He has received the NSF Presidential Young Investigator Award and the Fulbright Senior Scholar Award.

## Registration Information:

The fee for the two-day course is $450 prior to January 12, 2001. For registration after January 12, the fee will be $550. Student rates are $225 prior to January 12 and $275 after January 12.

**Registration forms and complete registration information are available at the Society of Rheology website, at:**

**http://www.rheology.org/sor/annual_meeting/2001Feb/**

10. D. Maier, A. Eckstein, Cr. Friedrich, J. Honerkamp, J. Rheol., **42**, 1153 (1998).
11. S.H. Wasserman, W.W. Graessley, J. Rheol., **36**, 543 (1992).
12. S. Wu, Polym. Mater. Sci., **50**, 43 (1984).
13. S. Wu, Polym. Eng. Sci., **25**, 122 (1985).
14. W.H. Tuminello, Polym. Eng. Sci., **26**, 1339 (1986).
15. D.W. Mead, J. Rheol., **38**, 1797 (1994).
16. Rheometric Scientific, Inc. Application Bull. 6a.
17. Rheometric Scientific, Inc. Product Brief "MWD1".
18. Rheometric Scientific, Inc. Product Brief "MWD2".
19. D.J. Plazek, N. Raghupati, S.J. Orbon, J. Rheol., **23**, 477 (1979).
20. K.A. Boni, F.A. Sliemers, Appl. Polym. Symp., No.8, 65 (1969).
21. G. Marin, F. Leonardi, "On the use of molecular models to derive the molecular weight distribution of linear polymers from viscoelastic measurements", Presented at the 71st Ann. Meeting of the Society of Rheology, Madison, WI (1999).
22. T.C.B. McLeish, J. Allgaier, D.K. Bick, G. Bishko, P. Biswas, R. Blackwell, B. Blottiere, N. Clarke, B. Gibbs, D.J. Groves, A. Hakiki, R.K. Heenan, J.M. Johnson, R. Kant, D.J. Read, R.N. Young, Macromolecules, **32**, 6734 (1999).

## RHEOLOGY BULLETIN AUTHOR GUIDELINES

The Rheology Bulletin publishes papers on the applied aspects of Rheology which are intended for the non-specialist. Appropriate topics include the application of rheological principles to a specific system, instrumentation for rheological measurements, description of interesting rheological phenomena, and the use of well-established rheological techniques to characterize products, processes or phenomena. Papers describing historical aspects of the practice of rheology and how these have influenced current trends are welcome. Also welcome are papers that address the present and changing status of rheological education. Consultation with the Editor prior to manuscript submission is encouraged.

## FUTURE MEETINGS OF THE SOCIETY

72nd Annual Meeting
Hilton Head, South Carolina
February 11 - 15, 2001

73rd Annual Meeting
Bethesda, Maryland
October 21 - 25, 2001

74th Annual Meeting
Minneapolis, Minnesota
October 13 - 18, 2002

## BOOK REVIEW

*AN INTRODUCTION TO ELASTOMER MOLECULAR NETWORK THEORY*

Arthur S. Lodge
Bannatek Press, P.O. Box 44133, Madison, WI 53744 (1999).
160 pages, $25 or 18 Sterling

In this monograph, which cna be considered as an extension of his earlier work on **Elastic Liquids (1964)**, Professor Lodge provides us with a critical, concise account of a molecular theory of condensed phase macroscopic behavior.

This work develops, from first principles, the required physics used in developing molecular theories of macroscopic properties of materials. In particular, a reasonably successful molecular theory of macroscopic rubber properties is described. Concepts and terms are clearly defined. Chapter 1 characterizes the rubber-like state. Chapter 2 deals with elastomers at the macroscopic level. The discussion is limited to homogeneous deformations. Chapter 3 deals with classical thermodynamics and uses body stress and metric tensors as generalizations of p and v. The term "equilibrium state" is treated as an undefined element. Chapter 4 is on statistical mechanics, introducing/reviewing ensembles, phase space, .... bridging molecular and macroscopic levels. These chapters dealing with continuum mechanics, thermodynamics and statistical mechanics are self contained. The tools presented are used in the (classical mechanics) derivation of constitutive equations. Chapter 5 introduces the Gaussian network theory while Chapters 6 and 7 provide the reader with a critical discussion of the theory deductions and available experimental evidence. Optical analysis is briefly mentioned but the references in this area are not up to date.

Very useful exercises are dispersed throughout. Solutions to these problems as well as further comments on the literature can be found in the appendices.

This work is relatively free of typographical errors and makes for a nice complement to an introductory rheology course which typically would deal only with topics such as generalized Newtonian fluids, rheometry and (mainly) linear viscoelasticity. This attractively priced monograph could also, quite nicely, be used in the context of an independent study course for students pursuing graduate work in rheology.

I enjoyed reading this presentation and plan to work it into the more advanced rheology course taken by Ph.D. candidates at Tulane.

Daniel De Kee
Department of Chemical Engineering
Tulane University

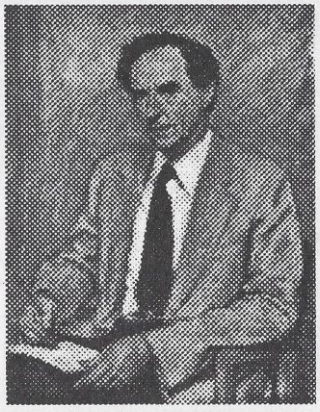
## Student-Member Travel Grants for Hilton Head

The Society is again offering travel grants to graduate student members to attend the annual meeting of the Society. Support is provided to defray the cost of public transportation to the meeting site. Interested student members may contact Dr. Lisa Mondy at Sandia National Laboratories concerning rules and eligibility. Dr. Mondy can be reached by telephone at (505) 844-1755 or by e-mail at lamondy@sandia.gov.

## George K. Batchelor, March 8, 1920 - March 30, 2000

With the passing of George Batchelor last March 30, at the age of 80, the international fluid mechanics community lost one of its most influential leaders who, by common consent, had dominated the field throughout the past five decades.

George was born in Melbourne, Australia, where he received his undergraduate education in Mathematics and Physics. In January 1945, after having spent the war years at the Australian Aeronautical Research Laboratory, where he focused on fluid-flow problems in aircraft engines, George embarked on a ten-week voyage via New Zealand, the Panama Canal and in a convoy across the Atlantic, reaching Cambridge, where he was destined to spend the whole of his academic career and the rest of his life.



George Keith Batchelor

His Ph.D. thesis on Kolmogorov's theory for the structure of small-scale turbulence, under the direction of G.I. Taylor, brought him instant recognition and established him as one of the rising young stars in fluid mechanics. In numerous subsequent papers and in his landmark monograph, "The Theory of Homogeneous Turbulence", George greatly expanded the theoretical underpinning of the field as well as its application to diverse areas such as heat transfer and the dispersion of particulates in turbulent atmosphere. But turbulence was not the only area of fluid mechanics in which George made seminal contributions, as a cursory glance at the Author's Index of the Journal of Fluid Mechanics will quickly ascertain. Indeed, the scope of George's deep knowledge of the whole of fluid mechanics is amply demonstrated by the contents of his masterful 1967 textbook, "An Introduction to Fluid Mechanics" which has already taken its place as one of the top classical fluid mechanics books to have ever been written. Of more relevance to the rheology community, however, are his numerous papers on particle motions at low Reynolds numbers where, inter alia, he developed an original and highly ingenious technique for renormalizing certain divergent integrals which are encountered invariably in the determination of the bulk properties of dilute suspensions. In this way, he was able to extend Einstein's famous formula for the effective viscosity of a suspension of spheres to the order $v^2$, where v refers to the particle volume fraction, and to derive in a rigorous way the first order correction to the hindrance function for sedimenting suspensions. He was also the first to show theoretically that a dilute suspension of aligned slender rods can increase dramatically its extensional viscosity while leaving its shear viscosity essentially unchanged.

George was more than an outstanding researcher, however. He was a superp teacher who educated a large number of students through his lectures and by acting as their Ph.D. advisor. Scores of them have already achieved international reputations of their own, and about a dozen or so of his former students have already been elected Fellows of the Royal Society of London. But his influence extended even beyond his role as a researcher and teacher, for, as is well-known, he created a school in Cambridge, eventually to become the Department of Applied Mathematics and Theoretical Physics, which quickly developed into a top fluid mechnics center on an international scale that attracted countless reseach students, post-docs, and international scholars, as well as senior seientists on sabbatical leaves. He was invariably suppportive of the visitors to his department, especially to the members of the younger generation, and the hospitality which he and his late wife Wilma extended to all of them became legendary.

In 1956, George founded the Journal of Fluid Mechanics which, from its inception, became the leading and most prestigious journal in the field, and served as its editor until a little over a year ago. He was a founding member and long-time chairman of the European Mechanics Committee, which was responsible for rejuvenating, during the post-war years, the mechanics activity throughout Europe, and served the International Union of Theoretical and Applied Mathematics in several capacities.

George was elected to the Royal Society, the U.S. National Academy of Sciences, and numerous other prestigious organizations, and received countless Awards and Honors. But what surely must have pleased him even more than such recognition is the realization that he had an enormous and very positive impact on fluid mechanics and on the lives of many of us.

George was the leader who led us into the promised land, the fascinating world of fluid mechanics. We are grateful to him for what he created and thankful that he made us a part of it.

**Andreas Acrivos**

## Bird Roasted

On February 4, 2000, Texas A&M University hosted a symposium in honor of University of Wisconsin (UW) Emeritus Professor of Chemical Enginering R. Byron Bird. Professor Jeffrey Giacomin of the University of Wisconsin delivered a lecture on Professor Bird's academic genealogy, called the Bird's nest. The roast included birthday cake, complete with trick candles, to celebrate Professor Bird's 76th birthday which was the following day. Held in Bird's birthplace, Bryan, TX, the banquet coincided with Charles Lindbergh's birthday. A hero of Professor Bird's, Lindbergh is the UW Mechanical Engineering Department's most celebrated former student. Giacomin, who flew in from Singapore for the event, pointed out that without trans-oceanic flight, the roast would have been impossible. Asked why he would fly so far for a banquet, Giacomin quipped, "I think we all like Bird well roasted."

The symposium consisted of a large number of technical lectures including one by Bird himself showing how mass flux in polymeric liquids can be affected by the flow field.

# The Society of Rheology

## Statement of Revenues and Expenses

## 1998 and 1999 Actuals, 1999, 2000 and 2001 Budgets

Units: USD

| | | 1998 Actual | 1999 Budget | 1999 Actual | 2000 Budget | 2001 Budget |
|---|---|---|---|---|---|---|
| 2. | ***REVENUES*** | | | | | |
| 3. | Dues | 83,903 | 59,000 | 58,440 | 61,000 | 68,000 |
| 4. | Interest | 36,527 | 37,000 | 32,347 | 38,000 | 41,000 |
| 5. | Journal of Rheology | 296,676 | 229,600 | 246,514 | 213,700 | 236,400 |
| 6. | Mailing List Sales | 6 | 300 | 130 | 300 | 300 |
| 7. | Bulletin Advertising | 1275 | 850 | 1913 | 850 | 1700 |
| 8. | Annual Meeting | 2417 | 5,000 | 0 | 0 | 0 |
| 9. | Short Course | 8351 | 4,000 | 0 | 4,000 | 4,000 |
| 10. | **TOTAL REVENUE** | **429,155** | **335,750** | **339,344** | **317,850** | **351,400** |
| 11. | | | | | | |
| 12. | ***EXPENSES*** | | | | | |
| 13. | AIP Dues Bill & Collect. | 8,304 | 8,500 | 9,391 | 9,000 | 9,800 |
| 14. | AIP Adm. Services | 9,000 | 9,000 | 9,000 | 9,000 | 9,000 |
| 15. | AIP Mem. Soc. Dues | 7,000 | 7,600 | 7,963 | 7,800 | 8,200 |
| 16. | AIP Financial Handling | 4,300 | 3,600 | 500 | 0 | 0 |
| 17. | AIP Phys. Olympiad | 1,500 | 1,500 | 0 | 1,500 | 1,500 |
| 18. | Misc. Contributions | 0 | 1,000 | 1,000 | 1,000 | 1,000 |
| 19. | Renewal Billing | 4,242 | 4,500 | 4,959 | 5,000 | 5,200 |
| 20. | Journal of Rheology | 299,354 | 233,600 | 262,357 | 241,900 | 261,050 |
| 21. | Bulletins and Abstracts | 19,170 | 13,000 | 17,555 | 13,000 | 12,000 |
| 22. | Short Courses | 4,773 | 3,000 | 0 | 3,000 | 3,000 |
| 23. | Bingham Award | 5,885 | 6,000 | 5,046 | 6,000 | 13,000 |
| 24. | Executive Cmt. Meetings | 7,045 | 7,000 | 7,758 | 7,500 | 7,600 |
| 25. | Pres. Discretionary Fund | 0 | 1,500 | 566 | 1,500 | 1,500 |
| 26. | Treas. Discr. Fund | 0 | 1,500 | 70 | 1,500 | 1,500 |
| 27. | Progr. Chm. Discr. Fund | 3,000 | 2,000 | 0 | 2,000 | 2,000 |
| 28. | Secretarial Services | 0 | 1,000 | 0 | 1,000 | 1,000 |
| 29. | Mailing | 40 | 4,000 | 4,407 | 4,000 | 3,000 |
| 30. | Office Expense | 469 | 2,000 | 507 | 2,000 | 1,000 |
| 31. | Banking Services | 129 | 250 | 137 | 250 | 250 |
| 32. | Liability Insurance | 250 | 1,803 | 2,647 | 1903 | 3500 |
| 33. | Membership Directory | 10,150 | 7,000 | 0 | 0 | 0 |
| 34. | Membership Broch. & Appl. | 741 | 0 | 578 | 1500 | 0 |
| 35. | Accountant | 1,597 | 1,700 | 1,517 | 1,800 | 1,900 |
| 36. | Student member travel | 5,500 | 6,000 | 3,214 | 7,000 | 7,000 |
| 37. | Adv. Dep. for future mtg. | 0 | 3,000 | 0 | 3,000 | 3,000 |
| 38. | Miscellaneous | 216 | 2,500 | 215 | 2,500 | 1,500 |
| 39. | **TOTAL EXPENSES** | **392,665** | **332,553** | **339,387** | **334,653** | **358,500** |
| 40. | | | | | | |
| 41. | Net Income | 36,490 | 3,197 | -43 | -16,803 | -7,100 |
| 42. | ASSETS (excl. reserves) | 173,583 | | 29,443 | | |

Notes:

2000 Budget as approved (with changes) by member vote at Madison meeting.

Line 8: Because the closing date for Madison meeting accounts was March 2000, the Actual for 1999 shows meeting and short-course revenues and expenditures of zero. The 2000 Actual will show the Madison meeting and short course revenues and expenditures, with a net of $19021.72.

Line 5: 1999 Actual includes $13,453 of CD sales. Revenue excludes subscriptions paid for future years. 2000 Revenue based on $550 subscription rate.

Line 20: Actuals include minor journal expenditures not paid through AIP.

Line 23: 2000 Budget is for Committee expenses; 2001 Budget includes two awards of $5000 each, plus expenses.

# Journal of Rheology

## Statement of Revenues and Expenses
### 1998 and 1999 Actuals and 1999, 2000 and 2001 Budgets

Units: USD

| 1. | 1998 Actual | 1999 Budget | 1999 Actual | 2000 Budget[A] | 2001 Budget[C] |
|---|---|---|---|---|---|
| 2. | | | | | |
| 3. Subscriptions | 211,036 | 195,050 | 201,845 | 186,000 | 204,250 |
| 4. Reprints | 8,406 | 9,800 | 10,334 | 7,800 | 10,800 |
| 5. Advertisements | 18,241 | 18,000 | 19,146 | 18,000 | 19,500 |
| 6. Electronic pub. [B] | 55,286 | 5,000 | 13,453 | 0 | 0 |
| 7. Miscellaneous | 1,127 | 1,750 | 1887 | 1,900 | 1,850 |
| 8. TOTAL REVENUES | **294,096** | **229,600** | **246,665** | **213,700** | **236,400** |
| 9. | | | | | |
| 10. Adver./Marketing | 8,839 | 9,800 | 9,266 | 8,500 | 9,100 |
| 11. Reprints, Singles | 8,437 | 8,300 | 10,686 | 9,000 | 11,300 |
| 12. Paper, Printing | 40,596 | 38,000 | 38,311 | 42,000 | 41,000 |
| 13. SOR Editorial | 46,617 | 45,000 | 50,555 | 49,000 | 50,000 |
| 14. Production | 72,818 | 75,950 | 87,428 | 79,000 | 78,400 |
| 15. Fulfillment | 7,876 | 8,250 | 7,953 | 7,900 | 7,950 |
| 16. Distribution | 20,671 | 20,300 | 22,868 | 22,000 | 24,200 |
| 17. Electronic pub. [D] | 92,861 | 28,000 | 35,290 | 24,500 | 39,100 |
| 18. TOTAL EXPENSES | **298,715** | **233,600** | **262,357** | **241,900** | **261,050** |
| 19. Profit | **-4,619** | **-15,692** | **-15,692** | **-28,200** | **-24,650** |

Notes:

[A] As modified and approved at the 1999 Madison meeting. Excludes recently approved back-file installation fee of $12,600 (estimate).

[B] Line 6, of 1998 and 1999 Actuals are from CD sales; JORO has virtually no income.

[C] Tentative budget. Assumes $550 institutional subscription rate.

[D] Line 17. Electronic publishing actual for 1999 is for Model 2, and includes a one-time upgrade fee of $7,600. 2000 Budget excludes one-time fees for back-issue installation and extra storage charges. 2001 Budget includes full storage charges for all back issues.

# The Society of Rheology
## Assets and Liabilities
## December 31, 1999

Units: USD

| | |
|---|---|
| **ASSETS** | |
| Cash in checking account | 10,735 |
| Balance in AIP account | 766,911 |
| | 777,646 |
| **LIABILITIES and RESERVES** | |
| Deferred subscription revenue | 141,827 |
| Deferred membership dues | 41,376 |
| Publication reserve | 450,000 |
| Student travel grant reserve | 10,000 |
| Annual Meeting reserve | 35,000 |
| Operating reserve | 70,000 |
| | 748,203 |
| Net available funds | **29,443** |

Notes: Publication reserve has been increased this year to cover long-term losses in revenue due to falling subscriptions, combined with increased costs due to JORO.

Respectfully submitted
Montgomery T. Shaw
Treasurer