

**A Report**  
**On**  
**NSF WORKSHOP ON PARTICLE SCIENCE AND TECHNOLOGY**

**Held On**  
**June 25-26, 1993**

**By**  
**R. Davies and R. Pfeffer**

**With Contributions From:**

**B. Ennis**  
**S. Pratsinis**  
**T. Allen**  
**G. Klinzing**  
**J. Carson**  
**G. Fuller**  
**D. Grant**  
**K. Leschonski**  
**L.J. Ford**

**A. Myerson**  
**D. Fuerstenau**  
**L.S. Fan**  
**L.T. Fan**  
**B. Moudgil**  
**G. Messing**  
**L.E. Manaster**  
**G. Jimbo**

**December, 1994**

**NSF Grant #CTS-9307456**

**NJIT**  
New Jersey Institute of Technology

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## SUMMARY

The NSF grant was awarded to accomplish two objectives:

1. To hold a workshop in particle science and technology to define the state of the technology in the USA and to design a path forward whereby U.S. manufacturing competitiveness in particle products and processes can be achieved.
2. To support the attendance of approximately 40 scientists and engineers at the first PTF meeting in Denver on August 17-19, 1994.

The Particle Science and Technology Workshop was held at NSF headquarters in Washington, DC on June 25 and 26, 1993. It was attended by 20 academics, 18 industrialists, nine government representatives and two AIChE organizers. Four of the 49 attendees were invited from overseas.

The objectives of the workshop were to:

- examine the relevance of the subject to U.S. manufacturing and competitiveness
- benchmark overseas competition from the viewpoint of education, research and technology transfer
- prepare a plan by which particle science and technology would be better coordinated in the USA, and
- through this plan improve the education, research and technology transfer in particle science and technology in order to make the USA more competitive with Europe and Asia.

The relevance of the subject to U.S. manufacturing and competitiveness was clearly shown by industrial speakers. In fact, particle technology was shown to be a core competency in many companies. Benchmarking presentations from three international speakers showed that:

- Particle technology was a requisite in the curriculum of process engineering degrees in Germany.
- Technology transfer between academia and industry in Japan was facilitated by well organized societies and associations having large industrial participation.
- A specially promoted SERC program in Particle Technology initiated in 1982 and supported for ten years, permitted the United Kingdom to organize the necessary interdisciplinary research needed to solve complex industrial particle processing problems.

In general the benchmarking showed that significant success had been achieved in Europe and Asia in the organization and pursuance of particle technology fundamentals

in education, research and technology transfer and that USA lagged behind them internationally in a field vital to U.S. industry. Action was needed to remedy the situation.

It was proposed that the organization responsible for the design and execution of a plan whereby the U.S. could begin to compete with its global competitors in particle technology be the Particle Technology Forum (PTF). PTF is an affiliated organization of the AIChE and is designed to cover a wide range of industrial disciplines relevant to manufacturing and materials. PTF is currently on a three year trial period, after which there will be a request for AIChE Division Status.

At the outset, PTF had 12 such disciplines. These were:

- Crystallization and Precipitation
- Size Reduction and Attrition
- Tribology, Friction and Interparticle Forces
- Fluidization and Multiphase Flow
- Particle Mixing, Segregation and Classification
- Dispersions and Interfacial Phenomena
- Particle Formation in Gases
- Size Enlargement and Agglomeration
- Particle Characterization
- Solids Transport and Handling
- Powder Mechanics and Solids Flow
- Suspension and Slurry Rheology

Other areas/disciplines proposed for consideration were: simulation and visualization, erosion, wear and deposition, but these were tabled for future consideration. Specialty areas strongly dependent on particle science and technology such as food processing, ceramics and pharmacy were also represented:

Presentations by the chair of each technical discipline were made to assess the current technical state of that area with regard to education, value to industry, research needs, and technology transfer. Two page summaries of these presentations are given in Appendices A-R and capsule highlights given in Section 6. Reviewing all 12 presentations, the major points of similarity were:

- Each technology was widely used in industry and was a critical stage in manufacturing processes.
- Industrial knowledge was often empirical and fundamental understanding was needed.
- Each technology had its links with some industries.
- The technologies were often isolated from each other partially because they were spread amongst several institutions who met independently.

- Though the particle technology subject in industry required interdisciplinary approaches to fundamental understanding and problem solving, this was seldom done.
- Input had to be provided from such areas as Chemistry, Physics, Chemical, Mechanical and Civil Engineering, Ceramics processing, Pharmacy, Food Science and Technology, and Material Science, and often small industries did not have the required diversity.
- Government research funding often followed similar lines in that multi-disciplinary teams were not assembled. In contrast, the requirement for such liaison was partly why the SERC special program in the UK was a success.
- Education in almost all particle technology related plant operations and processes was non-existent in overall engineering training. Vastly different to Europe, for example, where it is a requisite in Germany and the UK. for BS and equivalent degrees. However, a preliminary plan was developed and summarized in Section 8.
- Research needed in the field was specified by each speaker, but in this workshop, a research plan was not drafted as a consequence of insufficient time.
- Technology transfer between U.S. organizations needed to be improved. APPIE Japan had the best model and a U.S. adaptation of this model should be developed.

Following the presentations the subject of PTF organization and path forward was discussed. PTF was becoming an accepted organization but in its infancy. 1994 would require PTF to hold formal elections for a new executive committee and then develop a plan of action for the next five years.

Technology subgroup chairs and vice chairs had to be appointed and membership, both personal and industrial, had to be increased. The first major event to help launch this organization, define the election slate, and initiate a revised membership plan was PTF94 in Denver.

The inaugural meeting was a great success. Planning for 300 attendees, Denver attracted 450, and over 300 technical papers and posters were presented. The first PTF Technical Committee Meeting was held, an election slate prepared, and a membership drive initiated.

This NSF grant provided funds for more than 40 academics and engineers to partially offset expenses to attend Denver and to take part in planning the future of PTF.

As a result of the workshop, the next technology transfer event will be in 1996 in conjunction with the World Congress of Chemical Engineering in San Diego.

Another consequence of the discussions at the workshop was that Professor R. Pfeffer and his colleagues at NJIT submitted, and were awarded, two NSF grants entitled "Particle Technology in the Undergraduate Curriculum", and "Particle Technology in Manufacturing Processes", totaling \$400,000. Also, Professor B. Moudgil and his colleagues at the University of Florida (Gainesville) submitted a comprehensive \$20 million proposal to the NSF for establishing an Engineering Research Center (ERC) in Particle Technology. This was awarded in August of 1994, immediately following Denver.

It is felt that this workshop had a profound effect upon the future status of particle technology in the USA and several critical pieces are now in place to help the subject grow to national advantage.

## 1. Introduction

Interaction between the three primary phases of matter, solids, liquids, and gases influence significantly our environment and benefit our current lifestyle. These interactions occur at surfaces when the individual phases of matter are discrete in form. Particulates in the form of powders, emulsions, aerosols, foams, etc are the discrete components of these multiphase systems. The science and technology of these particulate systems can be shown to be critical to many products. Recently the U.S. Department of Commerce estimated that particulate products generate one trillion dollars annually to U.S. economy. DuPont alone, estimates that over 60% of its manufactured products rely heavily on particle science and technology, and add purchased particulates to another 20% of its products to gain end-use performance. DuPont products and processes therefore have only a 20% probability of not involving particle science and technology.

This pattern is typical of the Chemical Process Industries, indeed an estimated minimum of 40% or \$61 billion of the value added by the chemical industry is linked to particle technology, and particle technology is vital to many other sectors of the Chemical Process Industries, including advanced materials, food processing, mineral processing, and munitions, as well as energy, and the environment. New materials are driving developments in information communication, aircraft, space science, and biology. The superconductor industry alone is expected to reach a volume of \$150 billion/year by 2020. Grinding of particles or ores often is underestimated and, in fact, consumes 1.3% of U.S. electrical power production, and over 50% of this is devoted to minerals. So, shortcomings in powder technology harm the overall competitive position of the U.S. As we all realize, competitive pressures are intensifying. Indeed, it is becoming crystal clear that to successfully compete in the 21st Century will require low-cost manufacture of products having superior quality. Functional excellence becomes key to this process, and powder technology clearly is a paramount core competency to many sectors of our economy.

If particle technology is so important to the U.S. economy, let us, for a moment, consider the U.S. competitive position as it relates to the fundamental understanding of the science and technology of particles today.

Through the vision of Hans Rumpf in the mid fifties, Germany focused heavily on this technology and currently has 13 chairs in particle technology throughout the east and west. Japan is highly organized having 28 active research centers. The Society of Powder Technology Japan has approximately 1500 member and the Association of Powder Process in Industry and Engineering (APPIE) in Japan has an industrial membership of over 300 companies. Other international university chairs exist in Switzerland, Korea, Taiwan, the Netherlands, the United Kingdom and in Australia. **None exist in the USA.** The U.S. academic community has largely neglected particle science and technology both in research and education. This can be shown to be a factor in assessing faltering U.S. competitiveness and productivity. It prompted the preparation and publication of "A Legacy of Neglect" a position paper presented to heighten

awareness of the current situation, and to provide a focus for the newly formed "Particle Technology Forum" of the AIChE. This neglect has stimulated wide interest across the USA. It demands academia and industry begin to address the current problems and find solutions to them. This was the primary purpose for the workshop.

## 2. Workshop Purpose and Design

The Particle Technology Forum workshop was organized and held at NSF headquarters in Washington, DC on June 25th and June 26th, 1993. A copy of the Agenda for the workshop is attached as Appendix A. The workshop was attended by 49 experts in particle technology representing academia, industry, government, and professional societies. There were 20 participants from academia, 18 from industry, nine from government (including national laboratories) and two representing the AIChE. A list of all of the participants and their affiliations is attached as Appendix B.

The purpose of the workshop was to emphasize the importance of fostering research, education, and technology transfer in particle technology in order to keep the United States competitive with Europe and Japan in this important area of manufacturing.

## 3. International Benchmarking

The workshop began with introductions by Professor R. Pfeffer and Dr. J. Bordogna, Assistant Director of Engineering, NSF. This was followed by an assessment of the technology by Drs. B. Ennis and R. Davies. These talks were expanded and published as the cover article "Particle Technology - A Legacy of Neglect", April 1994 issue of Chemical Engineering Progress, Appendix C.

International perspectives were then presented by three speakers from overseas, addressing university/industry interaction, education, and university/industry collaborative research.

Professor G. Jimbo, Department of Chemical Engineering, Nagoya University, Japan outlined the organization and interaction of APPIE, the Association of Powder Process in Industries and Engineering, Japan. This was to give a model for industry/technology/university interaction.

The Association was established in November 1971 to provide an informal means of exchanging information on powder and bulk solid handling technology. Founded with fewer than forty members, the Association has increased its membership more than five-fold. The name in Japanese has been changed twice to reflect refinements in the Association's goals; and on December 1, 1981, the Association was authorized to operate as a corporate juridical person by the Japanese Ministry of International Trade and Industry.

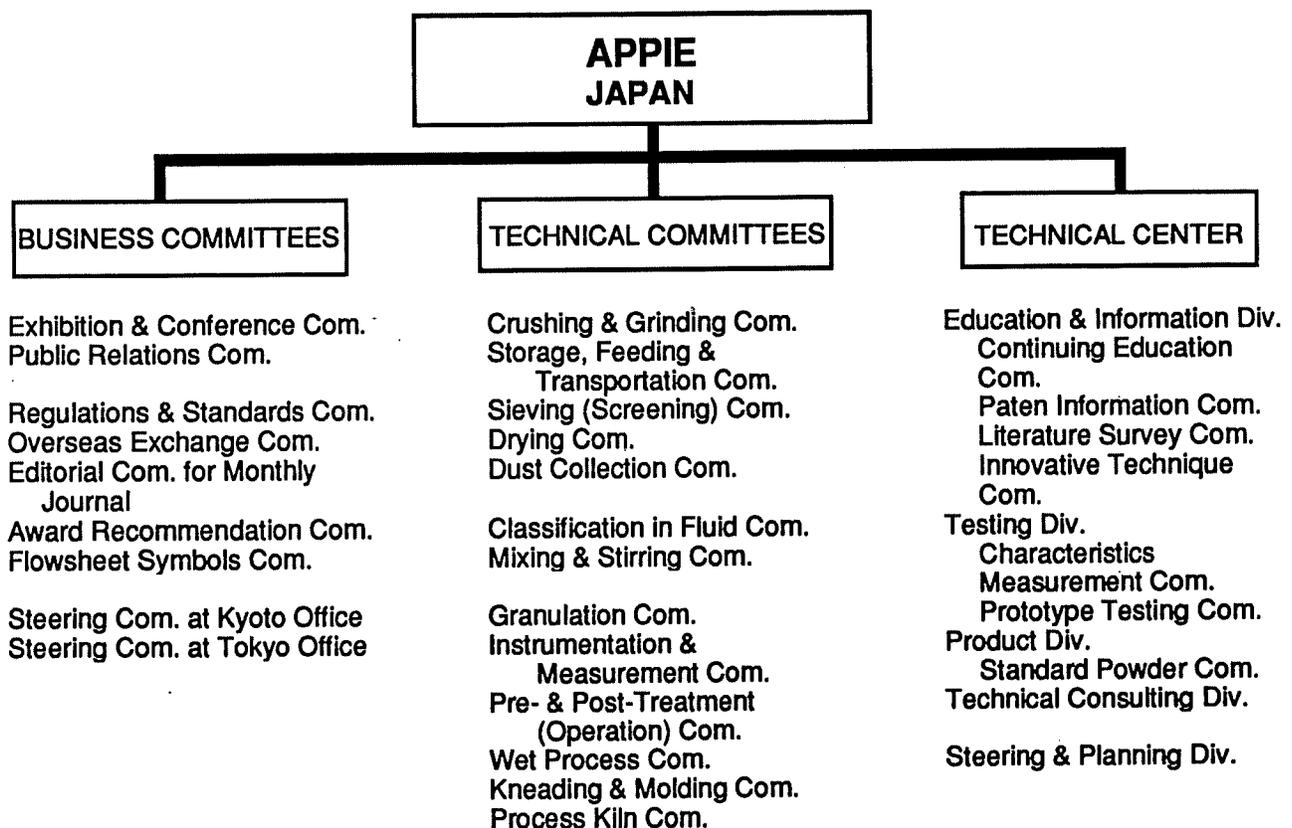
Organized and sponsored by the Association, the Japan Management Association, and three other organizations, the International Powder Technology Exhibition and Conference has been held in Tokyo every two years since 1976.

Today the Association has about 300 industrial company members, six sustaining company members, and 55 individual senior academic members.

The Association holds its annual business meeting in May, as well as four board of directors meetings and two general meetings in Tokyo or Kyoto every year. Informal evening parties to exchange information are held in Tokyo and Osaka alternatively every month. The "Tuesday" meeting is held in Tokyo, the "Thursday" meeting in Osaka.

The Association has three parts, which are composed of nine business committees, 13 technical committees and a technical center. The technical committees have edited and published many technical handbooks and manuals on powder and bulk solid handling processes. The technical and business committees are also planning to set technical standards.

An outline of the organization is given in Figure 1.



By many this is considered the model organization by which technology can be transferred between academia and industry and vice versa.

Professor K. Leschonski Institut für Mechanische Verfahrenstechnik, University of Claustal, Germany presented a capsule showing how particle technology appears in the engineering curriculum in Germany. Details of his charts appear in Appendix D.

The major points that emerged from the talk were that:

- Particle technology is a requisite in mechanical engineering Dipl. Engineering degrees in Germany.
- It is taught under process technology over a two year period.
- Approximately 140 hours are programmed for particle technology of which 56 hours are compulsory.
- Two courses on fundamentals are given to each student with additional laboratory experience.
- Other courses which cover specific aspects in more depth are offered and students can select from a course list.
- No student emerges with the Dipl. Engineering degree without fundamental knowledge of particle processes and laboratory experience.
- This does not occur in the USA.

Again the German model was viewed by many as the one to implement into U.S. education where possible. During the discussion which followed, it became clear that U.S. academics feel that this model would not find easy application into the U.S. system for various reasons to be discussed later.

The third international talk by L. J. Ford, IFPRI President and SERC Coordinator focused on specially funded research in the UK, in particular, the Specially Promoted Program in Particulate Technology funded by the Science and Engineering Research Council (SERC). The program was initiated in 1982 and ran for ten years. Grants were awarded for three years duration with a commitment of 0.5MM pounds sterling per year allocated to the total SERC program.

In general, the program struggled to find an industrial audience but was highly successful in drawing together grantees from multiple disciplines on each proposal to address the needs of the subject. Industrial interaction was achieved by holding open symposia on the projects every three to four years.

For the first six years, the special project focused on three principal areas:

1. The formation of particulate solids with controlled properties - any particle formation process is included but with additional emphasis on Aerosol Particle Production.

2. New/novel solid-liquid separation processes and Non Newtonian flow behavior.
3. The processing and handling of particulate solids at high solids concentration in gas/liquid media.

Gaps which were identified in the program were:

- a. Precipitation processes leading to controlled particle morphology.
- b. Impurity effects in growth processes.
- c. Agglomeration of colloidal and submicron particles to produce granules of controlled properties and role of sticky solids.
- d. Adhesion of particles to surfaces.
- e. Models which describe flocculation, sedimentation, and filtration which respond to changes in shape, interparticle forces and process variables.

The objectives were modified at the six year point, and the program extended for four additional years to:

1. Advance the understanding of how process equipment interacts with particles and determines the properties of particles produced, with particular reference to breakdown and growth processes as a function of the forces generated within the equipment.
2. Understand the relationship between the microscale physical and chemical properties and bulk assembly behavior, with special reference to the correct characterization procedures to be adopted in order that absolute, rather than empirical, relationships may be formulated.

The real benefit of this program was that it was multi-disciplinary and was not limited to engineers. Engineering disciplines provided the principal investigators, but grants had to have other disciplines. Grantees came from Chemistry, Physics, Chemical, Mechanical, and Civil Engineering, Ceramics, Pharmacy, Food Sciences, Mining, and Material Sciences. Another major advantage was that the coordinator had 30 years of industrial experience and had managed the ICI Particle Technology group. Many viewed this program as a good model for particle technology research, as the subject is multi-disciplinary, and needs a multi-disciplinary team to address many of the key problems. It did not require massive funding. Money was used as a lubricant to encourage diverse groups work together without friction toward a common goal. These talks were used to prompt discussion. The remainder of the workshop was focused on the thematic goals of the Particle Technology Forum and the planning of the First International Forum of Particle Technology to be held in Denver in August 1994. Let us now outline the objectives of PTF and its position in mid 1993.

4. Rationale for PTF

AICHE Group 3 "Contacting and Particulates, Operations and Processes" comprises of the following four subgroups:

Subgroup 3a - Mixing

Subgroup 3b - Fluidization and Fluid-Particle Systems

Subgroup 3c - Solids Flow, Handling and Processing

Subgroup 3d - Powder Technology

Subgroup 3a is a very active, demanding programming group. Its programming needs are now also served by another AIChE affiliate organization "North American Mixing Forum", which consists of large international constituents. The remaining groups, i.e., Subgroups 3b, 3c, and 3d, are core groups of the Particle Technology in the AIChE also dealing with Fluid Particle Technology, e.g., Subgroup 2f (Fluid-Particle Separation) and Subgroup 7e (Multiphase Flow). Fluid-Particle programs led by Group 3 have been very active for over two decades and have been steadily growing in strength. The Fluid-Particle Symposia at the AIChE Annual Meeting has remained over these years as one of the major forums in the field where a large number of high quality papers are presented. The symposia have their plenary lecture series, as well as annual recognition dinners. Most importantly, they are attended routinely by prominent researchers internationally. Numerous conference proceedings are published from these symposia, and are well in demand (an average of over 1000 copies sold for any recent issue).

Several factors necessitated the formation of this AIChE affiliated organization "Particle Technology Form". As the members of the Subgroups 3b, 3c, and 3d strongly desired that the fluid-particle symposia be held at the annual meeting (instead of national meetings), the current AIChE session allocation did not meet the programming needs of this field which is ever expanding. Furthermore, there was tremendous interest in the AIChE fluid-particle program by the international community. A number of international people wishing to solely affiliate with the fluid-particle group at the AIChE and participate in the group activity wanted to be able to pay only a nominal fee to become a member of the group without being burdened with a larger regular AIChE membership fee. More importantly, however, there was an urgent need to establish an organization which can serve as an international forum for this rapidly expanded interdisciplinary field of Particle Technology, and to foster and promote industrial and academic interactions.

The PTF was designed to cover a wide range of interdisciplinary topics in particle technology, and was initially structured around Subgroups 3b, 3c, and 3d; in due course it will expand to cover other areas such as mineral pharmaceutical and food processing, and include other disciplines besides chemical engineering. It is noted that the formation of PTF has been supported and endorsed by the Group 3 advisory committees, as well as many members in the subgroup committees. There are several very successful international conferences already in place

such as Engineering Foundation Conference on Fluidization and World Congress in Particle Technology. Thus, the meetings of PTF are not intended to compete with them. The PTF meeting will typically be arranged as the topical meeting in conjunction with the AIChE meetings. It will serve to facilitate expeditious exchange of ideas and information.

During the initial phase of the Forum operation, the following were appointed to serve in the Executive Committee:

L. S. Fan (Chair, Group 3), Ohio State University  
W. C. Yang (Vice Chair, Group 3) Westinghouse  
J. C. Chen (Chair, Group 3b), Lehigh University  
F. Thomson (Chair, Group 3c), DuPont (retired)  
C. Tien (Chair, Group 3d), Syracuse University  
M. Roco, National Science Foundation  
R. Pfeffer, NJIT  
R. Davies, DuPont (Chair, PTF Technical Committee)  
D. Keairns, Westinghouse

In summary, the important purposes of PTF are to accommodate participation of international members interested in particle technology, to bring increased awareness of leadership to AIChE in this field.

#### 5. NSF/PTF Workshop Goals and Organization

At the workshop in Washington, DC on June 25-26 ideas and strategic plans for PTF were requested in light of the previous international talks. Specifically, we wanted to:

- Address how the PTF as an organization will function, and how we will interact across disciplines.
- Address our initial technical subgroup organization as well as its philosophy and modify it where necessary. The technical direction for the PTF is established by a Technical Advisory Committee divided into specific subgroups to ensure equal representation and balance of both established and emerging research areas.
- Discuss the nature and frequency of special particle technology topics in AIChE's spring, summer, and fall meetings and discuss how this area might be better featured in future AIChE or other engineering society activities.
- Address the education and research issue and path forward. In particular, begin a process of benchmarking efforts in these areas.
- Finalize remaining details on the upcoming 1994 Denver conference, The First International Forum in Particle Technology.

To discuss these topics, we invited key individuals from academia, government, and industry from a spectrum of disciplines to the workshop. In addition, we invited international visitors from countries where national programs are already well established. The provisional technical subgroups and the proposed chairs for 1993/1994 are as follows:

- |  |               |
|--|---------------|
| • Particle Formation in Gases                    | S. Pratsinis  |
| • Crystallization & Precipitation                | A. Myerson    |
| • Size Enlargement & Agglomeration               | B. Ennis      |
| • Communication & Attrition                      | D. Fuerstenau |
| • Tribology, Friction, & Interparticle Forces    | M. Tirrel     |
| • Particle Characterization                      | T. Allen      |
| • Fluidization & Multiphase Flow                 | L. S. Fan     |
| • Solids Transport & Handling                    | G. Klinzing   |
| • Particle Mixing, Segregation, & Classification | L. T. Fan     |
| • Powder Mechanics & Solids Flow                 | J. Carson     |
| • Dispersions & Interfacial Phenomena            | B. Moudgil    |
| • Suspension & Slurry Rheology                   | G. Fuller     |

Additional participants were invited to represent key areas, including various representatives from DOE, NSF, and the National Labs. Some of these were:

Agglomeration	Kal Sustray, Univ. Cal., Berkeley
Ceramic Processing	Gary Messing, Penn State
Pharmacy	David Grant, Univ. of Minnesota
Canada	Stuart Savage, McGill Univ.
Germany	Kurt Leschonski, Univ. of Clausthal
Japan	Genji Jimbo, President Japanese Society of Powder Technology
United Kingdom	Les Ford, President International Fine Particle Research Inst.
Otis Walton	Lawrence Livermore National Lab
Stephen Dussman	Sadie National Lab

## 6. PTF Technical Subgroup Summaries

The following are short summaries taken from the two-page inputs given in the appendices.

### 6.1 Formation of Particles in Gases - Appendix F

- Widely used technology in industry.
- Academic/industry links good.
- Links between this subject and other particle subgroups not as good.
- Need for co-sponsored sessions, co-edited symposium, and technology exchange programs with multiple PI's.
- Interaction good with ceramics and materials groups.
- Education - nothing formal in the USA.
- Particle technology teaching fragmented.

- Need closer match of funded grants with industrial needs.
- Need cross fertilization of academic/industrial sabbaticals.
- Property rights is a barrier.
- Strong intradisciplinary following - World Congress in Aerosol Technology UCLA 1994 attracted 800 global attendees.
- Research needed.
  - Fundamentals of particle formation in reactive turbulent flows.
  - Measurement of fundamental properties including instrumentation development.
  - Transport properties of irregular particles.
  - Gas and surface chemistry during aerosol formation.
  - Innovative aerosol reactors

## 6.2 Crystallization and Precipitation - Appendix F

- Widely used technology in industry, next to comminution is probably the largest tonnage formation process.
- Academic/industry links good.
- Links between the subgroup and other Particle Technology subgroups not as good.
- Need for collaborative, interdisciplinary, exchange programs.
- Academically, the technical community is small but globally connected.
- Society/industry links have improved over the past five years as a result of AIChE, Association for Crystallization Technology, Crystal Growth of Organic Materials Group, Industrial Crystallization Working Party (European Federation of Chemical Engineers).
- Education in academia generally poor but variable.
- Research needed.
  - Control of batch and continuous crystallizers for PSD
  - Crystal shape - prediction and control
  - Impurity - crystal interaction
  - Management and control in Industrial Processes.

## 6.3 Size Enlargement and Agglomeration

- Widely used technology particularly in agriculture, pharmacy, food, and mining industries.
- Academic/industry links good.
- Links between subgroup and other technical subgroups not good.
- Cross fertilization of disciplines needed.
- Subject is a practiced art rather than a technology--lots written.
- Intrasubgroup technical links good.
- Education minimal.
- Research needs
  - Control and optimized steady operation of industrial granulators.
  - Better fundamental knowledge around bonding mechanism methods, mechanics, and the selection of additives.
  - Better knowledge of scale-up fundamentals.
  - Multi-disciplinary input required more often than today.

#### 6.4 Comminution and Attrition - Appendix G

- Very widely used technology--the largest tonnage producer of particles.
- Academic/industry links good.
- Links between subgroup and other technical subgroups not so good.
- Subgroup tends to be accentuated more in mining and materials symposium than in chemical engineering.
- Links with ASME critical.
- Cross fertilization of disciplines would be advantage.
- Education minimal in chemical engineering--more visible in mining.
- Research needs
  - There is a fundamental need for tailoring the properties of comminuted particle material to applications.
  - Fundamental understanding of single and multiple particle fractures.
  - Improved grindability test for small samples.
  - Improved knowledge of the interaction between the breakage device and the material fracture properties.
  - New energy-efficient technology.
  - Better dynamic modeling and entire plant simulation capability.
  - Better scale up knowledge.
  - Improved fine grinding technology.
  - Prediction of liberation characteristics.
  - Process control of comminution systems.
  - Classification for fine grinders.
  - Better control of wear in comminution devices.
  - Improved capability to comminute material for specific applications.
  - Understand the fundamentals of attrition in process equipment.

#### 6.5 Particle Characterization - Appendix H

- Widely used in industry.
- Vendor/industry links better than university/industry links.
- Four areas defined -
  - single particle systems, bulk systems
  - surface/chemical properties, bulk systems
  - mechanical properties, and
  - on-line systems.
- Links between this subgroup and other subgroups not good, but most people think they can characterize because of vendor/instrument availability.
- Education - nothing formal in the USA.
- Links with societies and industry wide and global.
- Research needs:
  - Instruments or methods for in-process measurement and links with process control.
  - Better standards needed for instrument comparison and calibration.

## 6.6 Fluidization - Appendix I

- Very widely used in industry.
- Academic/industry links very good.
- Global links very good--working parties in existence.
- Links between this subgroup and others needs to be improved.
- Education probably better than in any other subgroup.
- Thirteen universities cited as giving courses.
- AIChE links strongly established via Area 3B.
- Research needed
  - Gas-Solid Fluidization
    - Elasticity behavior of dense phase particles, or solids stress, in general, in fluidization stability analysis.
    - Flow behavior in bubble wake and voidage distribution around bubbles in analysis of gas flow division and bubble coalescence and breakup.
    - Gas kinetics theory approach in dilute and dense phase pneumatic transport simulation
    - Mechanism of cluster formation and dynamics of solids flow in core and wall regions and their interaction in fast fluidization.
    - Characterization of fluidization with fine powders
    - Scale-up criteria and fluidization at high temperatures and pressures.
  - Gas-Liquid-Solid Fluidization
    - Theoretical account of flow structure of three-phase fluidization or slurry bubble columns characterized by spiral bubble upflow and vortical liquid-solid downflow motion.
    - High velocity gas-liquid-solid fluidization
    - Numerical study of bubble formation, bubble rising, vortex shedding and macroscopic flow behavior of three-phase fluidization.
    - Scale-up and three-phase fluidization at high temperatures and pressures.

## 6.7 Solids Transport and Handling - Appendix J

- Very widely used in industry - a key technology for all processes from large scale (minerals) to small scale (pharmaceuticals).
- Academic/industry links quite good in places, but not widespread.
- Links between this subgroup and others is not good.
- Cross fertilization of other disciplines needed.
- Often the transport operation is left until last in a design and given little consideration.
- Control of these processes often lacking.
- Education is not common, but some universities have courses in the USA and most abroad.
- Research needs
  - Reliable control of processes.

- Synergistic designs - handling starts at the reactor and finishes at packaging - it is not only pneumatic conveying.
- Characterization of materials for design.
- Better knowledge of scale-up fundamentals, pressure effects.
- Feeder/bin interactions, pickup and saltation fundamentals, particle/particle interactions, electrostatic and drag effects.
- Better capability in fine particle handling.
- Reliable flow metering.
- Attrition and erosion control.
- Dense phase design improvements and better instruments for field use.
- Realistic modeling and simulation.
- Better understanding of heat transfer and solids flow.
- Further developments of optical methods for velocity and concentration measurements.
- Fundamental understanding of material effects.

#### 6.8 Particle Mixing, Segregation and Classification - Appendix K

- Widely used in industry.
- Can be a stand-alone operation.
- Mixing/demixing occurs in all other unit operations to some degree.
- Academic/industry links good - in USA via AIChE Mixing Forum.
- Solids mixing given probably less attention than liquid mixing.
- Was not cross fertilized well with other subgroups.
- Education primarily in continuing education and not in academia.
- Research needs
  - Current research done primarily in small companies/vendors and is empirical.
  - Better understanding of ways to mix materials with wide distributions of size, shape, and density.
  - Ditto for ultrafine cohesive particles.
  - Development of new methods, e.g., non-conventional and for continuous flow devices.
  - Development of in process analysis for mixture homogeneity including noninvasive sensors, i.e., tomography.
  - Understanding the role of process equipment design.
  - Better scale-up fundamentals.
  - Development of synergistic systems in which mixing is an integral part.
  - Analysis, modeling, and theory.

#### 6.9 Powder Mechanics and Solids Flow - Appendix L

- Widely used in industry for uncovering raw materials intermediates and final products.
- Links with industry, i.e., academics, and U.S. laboratories specializing in the measurement of flow properties is good.
- Interaction with other subgroups is not so good.

- Links within AIChE is good, but links with other societies needs improvement.
- Cross fertilization of disciplines would be an advantage.
- Education is lacking in academia in any regular course of study.
- Government funding is low in this area.
- Research needs fall under three major areas:
  - Better constitutive laws which enable one to map strains and strain ratios onto the stress state.
  - 3D computer programs to model, analyze, visualize, and simulate the stress state in equipment.
  - A better understanding of the bin load aspect of structural design. Need a detailed guidance concerning the various loading conditions, both static and dynamic which exist.
  - A recognition by government, industry, and academia of the importance of powder mechanics and solids flow to U.S. industry.

#### 6.10 Dispersions and Interfacial Phenomena - Appendix M

- Widely used in industry, coatings, paper, electronics, cosmetics, magnetic media ceramics, photography, etc.
- Academia not linked as well as some other subgroups.
- Interaction with other subgroups needed.
- Linked well with AIChE and other societies.
- Education fragmented at best.
- Research needs
  - Understanding particle/particle interactions to develop adequate process control.
  - Correlations between polymer conformation and particle/particle interactions.
  - Models with predictive capabilities
  - In-site characterization of dispersions, e.g., sensors, instruments
  - Decomposition and recycle characteristics of dispersants.
  - Influence of radioactive and biological effects on particle/particle interactions - environmental restoration studies.
  - Scale-up process optimization and control.

#### 6.11 Suspension and Slurry Rheology - Appendix N

- Widely used in industry.
- Fundamentals not obvious to industry. Technology transfer needed.
- Good national coverage.
- Well developed international community.
- Education varies widely - not consistently good.
- Research needed.
  - Simulation of suspension dynamics and structure.
  - Statistical mechanical based constitutive relations.
  - Continuum logical models.
  - Suspension structure measurements
  - Kinematic measurements

## 6.12 Tribology, Interparticle Forces - Appendix O

No information provided.

## 7. Special Technology Reports

### 7.1 Pharmacy - Appendix P

In pharmacy, pharmaceuticals is the field of study with which particle technology is most closely associated. Pharmaceuticals involves:

- a) The design, development, formulation and evaluation of delivery systems, i.e., dosage forms for drugs, the biological area of which is biopharmaceutics.
- b) The study of the physical and chemical properties and the stability of drugs and dosage forms which is termed physical pharmacy.
- c) The knowledge base for the manufacture and evaluation of dosage forms which is termed pharmaceutical technology or industrial pharmacy.
- d) The rates and amounts of absorption, metabolism and excretion of drugs in the body which is termed pharmacokinetics.

Undergraduate pharmacy courses in pharmaceutical particulate technology during the last two decades have suffered almost extinction in some colleges in favor of clinical, hospital and community pharmacy. Practical experience in handling particulate systems, e.g., particle sizing, powder flow, capsule filling and tableting are now lacking. However newer graduate courses in dosage form design and drug delivery are encouraging the introduction of particle technology and material science into graduate programs.

Pharmacy's interest in PTF include:

Short courses, workshops and seminars highlighting some specific areas of current and future interest to pharmaceutical particulate technology could involve virtually all subgroups of the forum. Examples could include: particle sizing problems and constraints; specific surface area measurements; powder flow; powder compaction (tableting); particle adhesion and cohesion; crystallization of pharmaceuticals; the challenges of high purity and high yield; production of ultrafine particles for inhalation (aerosol drug delivery systems); production of particles or powders with specific features.

To bring together pharmaceutical and other particle technologists and scientists and to link pharmaceutical research more closely with other

particle and chemical engineering areas, interdisciplinary or bridging meetings, seminars or workshops could be introduced. These activities could include plenary lectures focusing on specific areas, and contributed podium or poster sessions to provide forums for exchange of ideas and views.

## 7.2 Food Processing

Control of particle size during processing as well as in the finished product is a manufacturing necessity.

At present most disciplines using Particle Technology depend on the precepts of Powder Technology as a basis for extrapolation. Many industries can directly relate these precepts of dispersion and measurement into processing guidelines and product performance.

This is not easily done in the food industry where understanding the relationship between particle size and product performance is in its infancy. Competitiveness is directly related to cost effective processing, product performance, stability, appearance, and texture.

The Food Industry needs from Particle Technology:

- \*1) Adequate measurement techniques to enable measurement of all types, powders, liquids, and emulsions, of finished product. (This includes dispersed, non-dispersed, individual particles, and aggregates.)
- \*2) Benign dispersants to ensure measurement of particles and particle/particle interactions.
- \*3) Non-invasive methods/instruments to accurately measure individual particles.
- 4) Non-invasive methods/instruments to safely (within GMP guidelines) perform in-line measurements.
- \*5) Uniform calibration standards for instrumentation.
- 6) Better understanding and characterization of particle behavior/performance within foods.

Today there is no linkage, global or national, in Particle Technology between the Food Industry and Academia. Therefore food should be a subgroup within PTF. PTF, as an established organization under the umbrella of AIChE, offers the widest audience to readily reach/impact processing and performance issues.

There is an education void in Particle Technology in the United States and especially for the Food Industry. Courses relating Particle Technology to Foods are sorely needed as current education in this discipline exists as a part of another (i.e., Engineering, Chemistry, and Physics). Because each food product is a unique and dynamic system, reliable measurement requires specific knowledge of that system.

Specific food systems such as oil based, dairy, etc., may use common measurement techniques/methods. However, changes in raw materials, ingredients, ingredient suppliers, processing equipment parameters, processing equipment and shelflife time can produce data differences even in one product.

\*Attainable in the near future (<five years).

### 7.3 Ceramics

Particle processing is the single most important approach for fabricating both traditional and advanced ceramics. All subdisciplines of particle technology are utilized in fabricating these materials including powder synthesis, powder dispersion and surface chemistry, grinding, consolidation and shaping of powder masses from dispersions, pastes and dry powders, heating the materials to induce desiccation, etc.

The estimated world demand for advanced ceramics is \$13 billion (1987). I do not have a value for the size of the traditional ceramics industry. Electronic ceramics comprises nearly 85% of this value. Advanced ceramics find application in virtually all industries but have particularly large impact on the automotive, telecommunications, computer and chemical industries. The U.S. has seen its share of the electronics industry dwindle to less than 20% with most of the inroads coming from Japan. Many of the former U.S. suppliers are now owned by international concerns but nevertheless still supply to the U.S. industry. Clearly, those U.S. companies no longer manufacturing components and carrying out research will continue to fall behind until they are totally dependent on U.S.-based international suppliers.

Future employees in the ceramics industry are supplied by about ten universities that have core education programs in ceramics. Because this is a relatively small community, there are excellent linkages between companies and the universities. Many companies support research, participate in Centers and provide internship programs for undergraduate students.

The global (international?) linkages are good, because there are many international meetings in Europe and Japan about almost every facet of the ceramics field. The people in this field are knowledgeable about each others technical contributions. Again, the smallness of the field (i.e., the number of ceramics people) results in a fairly high awareness factor.

The AIChE is a large organization that does not appear to be user friendly. Although there are many areas where chemical engineers can contribute to the ceramics field, the AIChE venue is not an attractive site for learning and the dissemination of information. The AIChE meeting and the organization are simply too large. One easily gets "lost" in these meetings. If a sufficiently large portion of PTF can be focused on issues relevant to ceramics then it may become an attractive venue to the ceramics community. Otherwise, there are already many venues for the ceramics community to engage in information exchange. The topic is already flourishing elsewhere and thus it will be necessary to clearly identify new opportunities before AIChE-PTF can compete.

The level of education in ceramics is excellent but can still be strengthened in the area of particle technology. Typically, ceramic processing is not well covered in the universities. Part of the problem lies in the limited number of credits. Also, there are simply not that many people that focus only on processing and particle technology.

Research in ceramic processing ranges from simply applying basic knowledge from other disciplines to probing areas that are unexplored. A comprehensive review of research needs would take ten pages of single-spaced text. However, the trend to better process control through the use of improved and finer powders will continue for years to come. While the motivations are myriad, the lack of basic understanding of how processes operate for particles <500 nm is still a point of constant frustration in the industry. The attached list represents some of the other areas requiring attention.

#### Research Needs in Advanced Ceramics Processing

- Synthesis of discrete submicrometer powders of <500 nm diameter and particularly <100 nm.
- Synthesis resulting in DENSE, non-agglomerated particles.
- Comminution, separation, and classification of <0.5  $\mu\text{m}$  particles.
- Synthesis of dispersible powders (with dispersants added), so the manufacturer doesn't have to learn how to handle these powders.
- Modeling and characterization of particulate forming processes.
- More fundamental knowledge of the role of organic processing aids during forming.
- On-line evaluation and control of forming processes.
- Characterization of as-formed ceramic bodies.

#### 8. Education

Based on the contributions presented in Section 7, it is clear that one deficiency was the absolute lack of formal education in particle science and technology in the USA compared to many other parts of the world. This was debated extensively and the following course of action proposed.

- The lack of particle technology courses at U.S. universities was seen as a major void in chemical and mechanical engineering degrees.
- The UK., Japan, and Germany have better systems.
- Considering the difficulty of adding courses to a crowded curriculum, what could be done?

At the undergraduate level:

Beginning with the 15 universities at the workshop, tabulate:

- What PT courses are being given now and where.
- Collect and process data.
- Ask each industry present to give one to two undergraduate seminars to universities per year to increase awareness of PT.
- Ask each university present to consider preparing: 1) Examples of solids processing problems for insertion into curricula; 2) Prepare minors in PT; and 3) Prepare summer courses or electives in PT.
- It was proposed to recommend no directives to any of the above approaches but to leave each university the option to select the best approach to suit them.
- Ask industry management to "walk the talk" and support PT programs and student training.

At the graduate level:

- Offer special courses and expand the current lecture base.
- Speed this up by exchanging lecture notes from other U.S. or global universities with current courses.
- Industry offer solids processing internships - two/company/year

At the continuing education level:

- Review courses being given by industry and universities for various societies or professional advancement organizations.
- Draw up a list of credited courses--maybe 10-12 acceptable as a creditation in PT.
- These courses can be taken by anyone, and AIChE will credit them whether they have been taught by AIChE or not--providing that the teaching organization submits a letter confirming the attended course and the attendee.
- When the whole list of courses has been completed, an AIChE certificate will be awarded. Want industrial acceptance.

No timeline was established to achieve these goals, but it was left to the PTF administration to address these at a later time.

9. Research

Some program based on the SERC model was thought to be the best approach on which to base a research program. Cross disciplinary research and interaction was called for by almost all subgroups. The use of CRADA's was suggested. The government agencies present gave no encouragement for the chances of a specially promoted program to address needs. The matter was left undecided after the roundtable discussion.

10. Technology Transfer

10.1 The inaugural technical meeting of PTF was the Particle Technology Forum 1994 in Denver during August 1994.

The original budget allowed for 300 attendees and 250 papers and posters. Sixty percent of participation was from overseas. Appendix Q contains the Final Technical Program of PTF showing that 330 papers and posters were eventually presented with 450 attendees.

The second half of the grant award was to sponsor a number of academics who were presenting papers at the conference. Approximately 40 academic scientists and engineers issued NSF funds to partially cover their expenses to attend the conference.

10.2 At the conference, plans were made to hold the second PTF event in conjunction with the World Congress in Chemical Engineering in San Diego in 1996. The initial plan is given in Appendix R. NSF funding will be requested to support attendance at this meeting.

10.3 Other notable international conferences suggested for PTF support/collaboration were:

- PARTEC 95, Nuremberg, Germany, March 1994
- GRANULATION 97, PTF, USA
- Joint Conference, China, Japan, USA, 1995
- World Congress in Particle Technology, UK, 1998
- World Congress in Particle Technology, Australia, 2002

11. Interaction Across Other Societies and Between PTF Disciplines

Time ran out before this could be discussed at length. Agreement was reached that this should be done, but plans for its implementation were left for PTF committee activity.

PARTICLE TECHNOLOGY FORUM  
Workshop Sponsored By NSF  
AGENDA

Friday, June 25

**Introductions & Workshop Goals**

Bob Pfeffer, New Jersey Institute of Technology 8:00 am  
Joe Borogna, Assistant Director for Engineering, NSF 8:10 am

**Global Perspective & Grounding**

Led by Reg Davies, DuPont 8:20 am

What is Particle Technology?  
Bryan Ennis, DuPont 8:25 am

An Industrial Perspective on the Significance of Particle Technology  
Reg Davies, DuPont 8:55 am

Role Models of Academic & Industrial Collaboration in Japan  
Genji Jimbo, Nagoya University 9:35 am

Break 10:15 am

Education in Particle Technology  
Kurt Leschonski, TU Clausthal 10:30 am

The Specially Promoted Program in Particle Technology  
of the SERC, UK and IFPRI  
Les Ford, IFPRI 11:10 am

Wrap-Up and Discussion 11:50 am  
**Lunch** 12:00 pm

**Structure of the Technical Advisory Committee of the PTF**

Reg Davies 1:15 pm

**SubGroup Talks on Particle Technology Research in the US**

Led by Bob Pfeffer, NJIT and Mike Roco, NSF  
(12 minute slots) 1:30 pm

Particle Formation in Gases P. Stone  
Crystallization & Precipitation A. Myerson  
Size Enlargement & Agglomeration K. Sastry  
Comminution & Attrition D. Fuerstenau  
Particle Characterization T. Allen  
Particle Mixing, Segregation, & Classification L.T. Fan  
Powder Mechanics & Solids Flow J. Carson  
Break

3:00 pm

Tribology, Friction, & Interparticle Forces D. Smith  
Dispersions & Interfacial Phenomena B. Moudgil  
Suspension & Slurry Rheology G. Fuller  
Fluidization L.S. Fan  
Solids Transport & Handling G. Klinzing  
Multiphase Flow J. Sinclair

3:15 pm

**Particle Technology Perspectives by Discipline**

Reg Davies, DuPont 4:30 pm  
Ceramic Processing Gary Messing  
Pharmacy David Grant  
Food Processing  
National Labs Otis Walton & others

**Wrap-Up**  
Dismissal

6:00 pm  
6:30 pm

**Break out Discussions around Education, Research,  
and Collaboration**

Evening over  
Dinner

**Saturday, June 26**

**Thematic Goals of the PTF over the Next Three Years**

Led by L.S.Fan and Reg Davies

Introduction and Goals of the PTF  
L-S. Fan, Ohio State University

8:00 am

Discussion of the Technical Advisory Committee of the PTF

Reg Davies, DuPont

Summary of Subgroup Discussion

8:20 am

Round Table Discussion:

9:00 am

Topics:

Education

Research

Interaction across disciplines

Conference activities

Industrial, academic, government collaboration

International activities

Interaction across other societies

Chi Tien

American Filtration Society

M. Roco

ASME-MultiPhase Flow

Break

10:45 am

Organizational Plans of the PTF

L-S. Fan, Ohio State University

11:00 am

Topics:

Membership

B. Ennis

Programming

W. Yang/B. Ennis

Newsletter

W. Yang

Awards

W. Yang

World Congress of

Chemical Engineering

P. Knox

**Lunch Break**

12:00 pm

**The First International Forum of Particle Technology**

Led by R. Davies, B. Pfeffer, M. Roco, & B. Ennis

Reg Davies, DuPont

Introduction

1:00 pm

Bryan Ennis, DuPont

Status: Structure

1:20 pm

Invited speakers

Co-sponsorship

Advertising

Proceedings

Bob Pfeffer, NJIT

Peter Knox

Funding & Budgeting

Discussion

2:00 pm

**Departure**

3:00 pm

ATTENDEES

APPENDIX B

Particle Technology Forum Workshop  
NSF, Washington, DC, June 25-26, 1993

<u>Name</u>	<u>Affiliation</u>	<u>Phone</u>	<u>FAX</u>
Ahart, Robert	Unilever R&D	201-943-7100 X2693	201-943-7649
Allen, Terence	DuPont	302-366-2159	302-366-4889
Beimesch, Wayne	P&G	513-853-2446	513-853-2465
Bieber, H.	Hoffmann-LaRoche Inc.	201-835-3192	201-235-7318
Carson, John	Jenike & Johanson	508-392-0300	508-392-9980
Coulaloglou, C.	Exxon R&E Co	201-765-6775	201-765-7789
Crowe, Clayton	Washington State Univ.	509-335-3214	509-335-4662
Davies, R.	DuPont	302-695-2839	302-695-2504
Ellis, Gordie	AICHE - Headquarters	212-705-7328	212-752-3297
Ennis, Bryan	DuPont	302-695-3835	302-695-7804
Fan, L.S.	Ohio State University	614-292-7907	614-292-1929
Fan, L.T.	Kansas State U.	913-532-5586	913-532-7810
Ferrell, Frank M.	U.S. Dept. of Energy	301-903-3768	301-903-8350
Ford, Les	U.K.	(44)51-420-1850	(44)51-424-1495
Fuerstenau, D.	U. California-Berkeley	510-642-3826	510-642-6623
Fuller, G.	Stanford University	415-723-9243	415-725-7294
Grant, D.	U. of Minnesota	612-624-3956	612-624-2974
Jacob, Karl	Dow Chemical	517-636-5706	517-636-4616
Jimbo, G.	Nagoya U.-Japan (Chubu Powtech Plaza Lab)	(81)-52-586-5643	(81)-52-586-5676
Joseph, D.	U. of Minnesota	612-625-0309	612-626-1558
King, Desmond	Chevron	---	415-242-5016
Klinzing, G.	U. of Pittsburgh	412-624-9814	412-624-1108

Knowlton, Ted	PSRI	312-225-2525	312-225-7818
Knox, Peter	AIChE	212-705-7338	212-752-3297
Leschonski, Kurt	Technical University.- Claustal Germany	011-49-5323-722309	011-49-5323-83804
Lyczkowski, Robert	Argonne Nat'l Lab	708-252-5923	708-252-5210
Malghan, S.	NIST	301-975-6101	301-990-8729
Manley, O.	DOE	301-903-5822	301-903-6594
Matson, John	Exxon R&E Co.	201-765-6778	201-765-1188
Messing, G.	Penn State University	814-865-2262	814-865-2917
Moudgil, B.	University of Florida	904-392-6670	904-392-6359
Myerson, A.	Polytech U.-N.Y.	718-200-3620	718-260-3136
O'Rear, E.	NSF	202-357-9606	202-357-5184
Passman, Stephen	Sandia Nat'l Lab	505-844-7686	505-845-9500
Pfeffer, Robert	NJIT	201-596-3429	201-596-6479
Ranade, Arun	Particle Tech. Inc.	410-712-7138	410-712-7058
Roco, Mike	NSF	202-357-9606	202-357-5184
Roha, David	Alcoa	412-337-3943	412-337-4063
Rosner, Dan	Yale University	203-432-4391	203-432-7232
Sastry, K.	U. Calif.-Berkeley	510-642-3808	510-643-5792
Sinclair, J.	Carnegie Mellon	412-268-3020	412-268-7139
Smith, Douglas T.	NIST	301-975-5768	301-990-8727
Stein, Louis	Shell Dev. Corp.	713-423-7277	---
Stone, Paul	Dow Chemical	202-429-3440	202-429-3467
Tien, Chi	Syracuse University	315-443-4050	315-443-2559
Tsuji, Y.	Osaka University	(81)-6-877-5111	(81)-6-876-4975
Walton, O	University of California Lawrence Livermore Nat'l. Lab.	510-422-3947	510-422-3118
Yang, W.C	Westinghouse	412-256-2207	412-256-1948

# The Legacy of Neglect in the U.S.

**M**uch of our environment and the benefits that we derive from our surroundings are strongly influenced by the interaction of the three primary phases of matter — solids, liquids, and gases. These interactions often occur at surfaces with the individual phases of matter being discrete in form. Powders, both wet or dry, are one very important

example of such a multi-phase system. As with solids, bulk powders can withstand deformation. As with liquids, they can flow. And, as with gases, they exhibit compressibility. The macroscopic behavior of a powder is controlled by the interactions of the individual particles, which can range in size from nanometers to centimeters. These interactions include adhesion and friction among the particles themselves, as well as interactions with any surrounding liquid or gas. Our familiarity with particulates includes such common examples as the color of the sky at twilight, sand castles on a beach, and the hourglass. In addition,

powder technology plays an important role throughout the chemical process industries (CPI), including in such diverse areas as agricultural chemicals, foods, pharmaceuticals, minerals processing, and advanced materials. Yet, U.S. manufacturing processes involving the handling of powders have been estimated to rarely reach more than 60% of their design capacity (1).

In this article, we review the historic economic importance of powder technology from a perspective to the development of chemical engineering. We describe a basic approach to standing powders that relates microscopic particle properties to the bulk behavior of powder. We then present a brief overview of the operations of powder processing, as well as a systems approach is appropriate to powder processes. Future trends in research education are highlighted along the way.

## Historical perspective

Mankind from its earliest times has derived benefits from particulate systems. For instance, the Egyptians relied on an enormous series of canals and flood basins to control silting of the Nile river. The silts deposited in the flood basins not only supported the thriving agriculture along the Nile, but also provided the raw ingredients for brick and early ceramic handicrafts (Figure 1). Other examples of particulate technology in Egyptian life were the winnowing and crushing of grain, followed by the kneading of flour. Crushing also was employed to liberate precious metals and gems. Egyptian examples of colloid rheology include the mixing of black soot with water and the preparation of an edible gum for ink, and the production of paper from mud, sand, and straw.

The production of pottery and milling of grain for bread (Figure 2) were to become leading industries for many generations. The growth of the disciplines of mining, mineral processing, and metallurgy further increased our familiarity with particulates and the processing of powder. The understanding of soils played a large role in the

shaping of civil engineering. Particle processing has spurred the industrial revolution and the birth of the CPI. chemical enterprises vi

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*While other nations have long recognized the importance of powder technology, the U.S. lags seriously behind. Industry, government, and academia all must play key roles if we are to improve our mastery of powders — and our competitiveness.*

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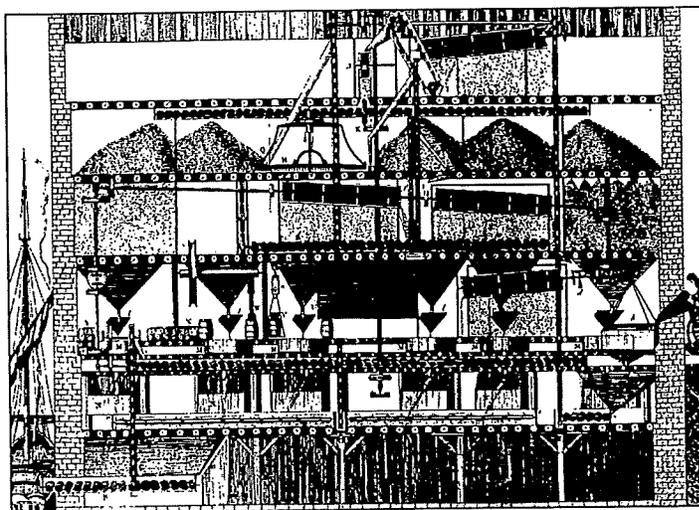
**Bryan J. Ennis, John Green, and Reg Davies,**  
E.I. DuPont de Nemours & Company, Inc.

the economic growth of the American colonies included potash, indigo dye, salt, saltpeter, gunpowder, lamp black, and white lead. The preparation of indigo in the late 1600s involved controlled precipitation of dye particles, which involved simultaneous fermentation and oxidation, followed by filtration, evaporation to a paste, drying, and compaction into cakes. Saltpeter, an important ingredient for gunpowder, is an early example of crystallization of potassium nitrate from refuse. The production of gunpowder from which the DuPont Company grew is essentially a controlled milling process. In the early 1700s, the production of lamp black began in New York and was a predecessor of today's aerosol reactor technology. Early manufacture of paints and pottery relied extensively on pigments made from zinc and white leads.

### The emergence of chemical engineering

As demand from merchants for specialty products grew, so did the need for chemical suppliers. These producers started to focus on economies of scale. When engineers and industrial chemists began to recognize that key phenomena were universal to all processes, and that many of the processes or "unit operations" were common to many industries, chemical engineering emerged as a profession (2). While the British often are credited for introducing unit operations, Americans promoted widespread adoption of the concept. By the beginning of this century, America's focus was on mass production, and the equipment and apparatus used in chemical production. Strong ties existed between chemical engineers and other disciplines involving significant mechanical processing, such as mineral or metallurgical production. As a result, the first chemical engineers were introduced to the early concepts of particle technology, with a strong focus on machine design. This is evident from early American chemical engineering textbooks, such as those of Walker, and Badger and McCabe, that devoted 40% of their content to particle processing (3,4). While Americans focused on mechanical processing, Germany introduced chemical science, namely, physical chemistry and thermodynamics, into chemical production. The importance of

■ *Figure 1. A portion of a wall painting from an Egyptian tomb showing Egyptian pottery manufacture (36). Clay minerals were mechanically ground. Tempers were added to control plasticity, shrinkage, and porosity. The ground powders were classified either by manual screening or by flotation (37).*



■ *Figure 2. Flour mill at Occoquan, VA, 1795. Conveying apparatus raises wheat to the top floor. It then descends through a rotating screen and fan, where chaff is blown away, to bins, and finally to one of six millstones. Elevators then raise the ground meal so that it can be fed to bolting screens, where flour and middlings are separated. Courtesy: The Hagley Museum, Wilmington, DE.*

these contributions generally has led to Germany being considered the seedbed of modern chemical engineering. These chemical sciences, however, are far from sufficient for successful chemical engineering.

Germany's strong emphasis on mechanical processing did not occur until the 1960s, due particularly to the efforts of Hans Rumpf (5). He identified three classes of process technology: chemical transformations by reaction; phase transformations governed by thermodynamic equilibria; and physical or mechanical transformations in the state of disperse systems or mixtures — powders being one important example. Rumpf pioneered the development of mechanical process technology as an integral part of

German chemical engineering, and his efforts represent the birth of particle technology as a coherent field in post-war Europe.

While Rumpf often is called the founder of particle technology, the first treatise on the behavior of particulate materials is that of J. M. Dallavalle in the U.S. In his 1943 book "Micromeritics: The Technology of Fine Particles" (6), Dallavalle for the first time brought together the scattered information dealing with particle-size measurement, particle packing, and the general theory concerned with the physical properties of finely divided substances. He demonstrated the scope of the field by drawing on literature from soil physics, mineral processing, chemical engineering, geology, hydrology, wind storms, pigments, and ceramics. Dallavalle outlined the proper methods of particle-size analysis long before the classic text of Allen (7). He treated the issue of the bulk properties of powder under pressure before the pioneering work of A. Jenike of the 1960s (8). He dealt with particle wetting and surface properties before G. Parfitt (9), and introduced fracture mechanics into grinding before Rumpf.

### The U.S. lags behind

Despite Dallavalle's vision, the U.S. hardly has progressed in incorporating particle technology into education. In contrast, following World War II, Japan, led by Iinoya, among others, made particle technology research a priority for its universities, and relied on Dallavalle's book "Micromeritics," which was later translated into Japanese. Today, the Japanese Society of Powder Technology, which has nearly 1,500 members, and the Association of Powder Process Industry and Engineering, an industrial consortium of over 300 companies dedicated to particle research, testify to the stature of particle technology in Japan.

Many Japanese and German universities have developed powder technology departments with strong industrial

support. There are 28 active research programs in Japan, and 13 particle research chairs in Germany, as well as four in the U.K. (10). Japan also has sixteen government research institutes undertaking particle research. Chairs in particle technology exist in other countries, as well — including Switzerland, Korea, Taiwan, and The Netherlands. In contrast, the U.S. academic community largely neglects particle science and technology, both in research and in education. This seems to be particularly telling input in assessing faltering U.S. competitiveness and productivity.

***Indeed, an estimated minimum of 40%, or \$61 billion, of the value added by the chemical industry is linked to particle technology, and particle technology is vital to many other sectors of the CPI.***

### Economic impact

Particles are critical to most products. For instance, in 1985 and again in 1992, DuPont found that 62% of its 3,000 products were powders, crystalline solids, granules, flakes, dispersions, slurries, and pastes. A further 18% of the products incorporated particles to impart key end-use properties. These particle products span the entire range of DuPont businesses: basic chemicals, agricultural products, pharmaceuticals, paints, pigments, dyestuffs, ceramics, and electronic materials. This pattern is typical of the CPI. Indeed, an estimated minimum of 40%, or \$61 billion,

of the value added by the chemical industry is linked to particle technology (11), and particle technology is vital to many other sectors of the CPI, including advanced materials, food processing, mineral processing, and munitions, as well as energy, and the environment. New materials are driving developments in information communication, aircraft, space science, and biology. The superconductor industry alone is expected to reach a volume of \$150 billion/year by 2020 (12). Grinding of particles or ores often is underestimated and, in fact, consumes 1.3 % of U.S. electrical power production (13), and over 50% of this is devoted to minerals.

So, shortcomings in powder technology harm the overall competitive position of the U.S. As we all realize, competitive pressures are intensifying. Indeed, it is becoming crystal clear that to successfully compete in the 21st Century will require low-cost manufacture of products having superior quality. Functional excellence becomes key to this process, and powder technology clearly is a paramount core competency to many sectors of our economy.

### Demystifying powder behavior and particle properties

Our understanding of powder behavior, despite its economic importance, remains limited compared to other classes of materials or disperse systems. The implications of this state of affairs are twofold. First, the design, startup, and processing of powders continues to be a difficult endeavor. Second, products involving particulates often are produced with substandard quality or end-use properties (frequently because of a somewhat misguided focus on process yields).

Both problems often arise because engineers settle for "art" or, at best, empiricism, because they don't think there are guiding themes or unifying concepts available. In fact, however, much is known and understood, though difficult. It all begins by realizing that powders are composed of

particles with a set of key attributes, and these attributes or properties determine the behavior of the powder as a whole.

A powder consists of particles that have a morphology, and certain bulk and surface properties. Paramount in controlling the behavior of powders is particle size. Size dictates the relative magnitude of surface-to-volume forces acting on the particle, and it is this competition of forces that controls many phenomena involving discrete systems.

We are familiar with some of these phenomena. Sand flows predictably through an hourglass. Pouring flour from a bag, however, is not so well controlled. There are many examples of unexpected powder behavior. For instance, if one shakes a canister of sand into which several marbles have been added, the marbles will eventually rise to the top, despite their larger size and density. Powders when sheared expand in volume; this dilation is observed firsthand by the temporal footprints left in wet sand along a beach. Biological activity of many pharmaceutical powders can be controlled by particle size: wafarin is a rat poison when a fine powder but, when tableted, controls the release rate in the intestinal tract and becomes an effective treatment for heart disease. The size distribution of titanium pigment must be carefully controlled: too fine a size results in loss in hiding power, whereas too coarse results in a loss of the blue hue exhibited by high-quality paints.

First and foremost are *morphological considerations*, which include the size and shape of a particle. Additional morphological properties include surface area, both internal and external, large-scale roughness and asperities, flaws or defects, both bulk and surface, and compositional homogeneity. Following morphological considerations are a set of properties that collectively affect the *contact mechanics* or *short-range interactions* of particles. These include surface energy and adhesion, surface friction,

electrical/magnetic contact and charge-transfer properties, bulk and surface hardness, and elastic moduli. It is the contact mechanics or short-range interactions of particles that control both the behavior of assemblies, as well as single-particle interactions in more dilute systems. In dilute systems, we encounter a set of properties that collectively control *long-range particle interactions*, which include the surrounding medium. We now will delve deeper into each of these considerations to provide a better appreciation of the current principles, hurdles, impact on powder processing, and future research directions.

### Composition

At the heart of defining all the above properties are compositional considerations, both chemical and physical. In the end, it is how we have built up the chemical composition and structure of a particle, as well as modified it in subsequent processing, that control the properties described earlier. From a conventional analytical point of view, the composition often is described as some percent purity. This, however, neglects two important points: first, this composition describes the interior of the particle of which little contributes to the surface; and, secondly, surface impurities at concentrations as low as ppms often may dominate the behavior of the particle. Of equal importance to behavior of a particle is its distribution of flaws or defects as discussed below.

We can consider three types of particles:

*Single particles* either may be amorphous, such as with some polymers, or single crystals that reflect the crystallography of the unit cell. For crystalline materials, faces can have differing surface chemistry. Single crystals are often an indication of high purity, and a well-controlled process. They frequently are found with inorganic systems, such as sodium chloride, ammonium sulphate, or potassium nitrates, where the crystallization

is dominated by strong Coulombic interactions. In organic crystallization, achieving single crystals in practice is more difficult as the intermolecular interactions often are dominated by weaker Van der Waals forces.

*Aggregates* commonly are formed in which a particle is comprised of many smaller, often randomly oriented, single crystals or amorphous particles. (Van der Waals forces play a crucial role in contributing to both adhesion between surfaces, and long-range particle interactions; they, in turn, depend on the chemical composition of the material and so can be modified in the formation process.) Aggregates arise from the existence of impurities or rapid crystallization; they may or may not be desirable depending upon the desired product attributes — for instance, grinding, biological efficacy, and flowability. Powders composed of aggregates behave very differently from single crystals, and are found in many pharmaceutical, agricultural, and pigmentary powders. As an example, a magnetic audio or visual tape is coated with magnetic particles that are single-needle-shaped crystals that behave as individual bar magnets. These crystals are obtained by milling aggregates. Aggregates are very difficult to break and typically have very little internal surface area, unlike powder agglomerates.

*Powder agglomerates*, in contrast, may consist of similar or dissimilar particles bound together, perhaps by an agglomeration process, through liquid bridging, then drying. The chemistry of the constituent particles, as well as the agglomerate's porosity help define its behavior, examples being dissolution rate of pharmaceutical granules, and the attrition rate of catalysts.

Better knowledge of the compositional aspect of particles should allow the synthesis of new molecules having special properties and, perhaps more importantly, should enable control of how these and existing molecules are presented. Now, in some cases, unintentional impurities

confer useful morphological behavior; this is unacceptable, and we should aim to take charge. This brings us to *engineered particles* in which the morphology, habit, and surface of particles are designed so that the desired behavior is achieved. The growth and implementation of crystal habit modeling is an important step. It provides a basis to design or select additives and the influence of solvent in the control of polymorphs and crystal shape. This is important in commercial processes (14,15), such as manufacture of silver halide crystals for photographic emulsions, and the design of wax crystal modifiers for diesel fuels. Current calculation methodologies require crystal structure data for model prediction. The influences of solvent on morphology then may be considered, although this is complicated by the need to account for solvent molecule orientation. Other challenges include prediction of crystal structure from molecular data, and morphological predictions for inorganic systems based on lattice energy calculations, which are particularly difficult.

### Surface energy and dispersion properties

Because molecular interactions lead to a reduction in free energy, the surface energy of a solid is that excess energy resulting from surface molecules having fewer neighbors compared to those in the bulk. This surface energy, for example, drives particles to reduce their surface area by becoming spherical. A molecular approach to estimating the surface energy of a particle would be formulated by the summation of all intermolecular forces between that surface and the surrounding liquid or gas. Cataloging these forces is nontrivial as they include:

1. Coulombic forces due to surface charge, whether from ionization of surface groups when dispersed in liquid medium or from electrostatic charging of dry powders; and
2. Van der Waals interactions.

For the simple case of Van der Waals interactions alone, the surface energy  $\gamma$  can be formulated as  $\gamma = A/24\pi(0.165 \text{ nm})^2$  with  $A$  being the Hamaker constant. Unfortunately, the surface of real powders is complex, having many different chemical groups, impurity chemical species, lattice defects, and topographical subtleties. Each of these contributes to an overall energy, but is intractably complex at present. One must instead resort to measurement techniques, as discussed below, to experimentally characterize surfaces. It is important to understand, however, that particles interact via surfaces, and surface energy contributes significantly to adhesion and friction phenomena, as well as to long-range particle interactions that affect dispersion stability, and that surface energy can be modified or tailored.

For disperse systems, *DLVO theory* is used to describe the interparticle interactions in liquids. The total potential energy of interaction  $w(d)$  between two spherical particles of radius  $a$  at constant potential is computed from the sum of the repulsive Coulombic potential less the attractive Van der Waals potential (see Equation 1).

$$w(d) = \frac{64\pi k T a \rho_{\infty} f(\zeta)^2}{\kappa^2} \exp(-\kappa d) - \frac{Aa}{6d}$$

#### ■ Equation 1.

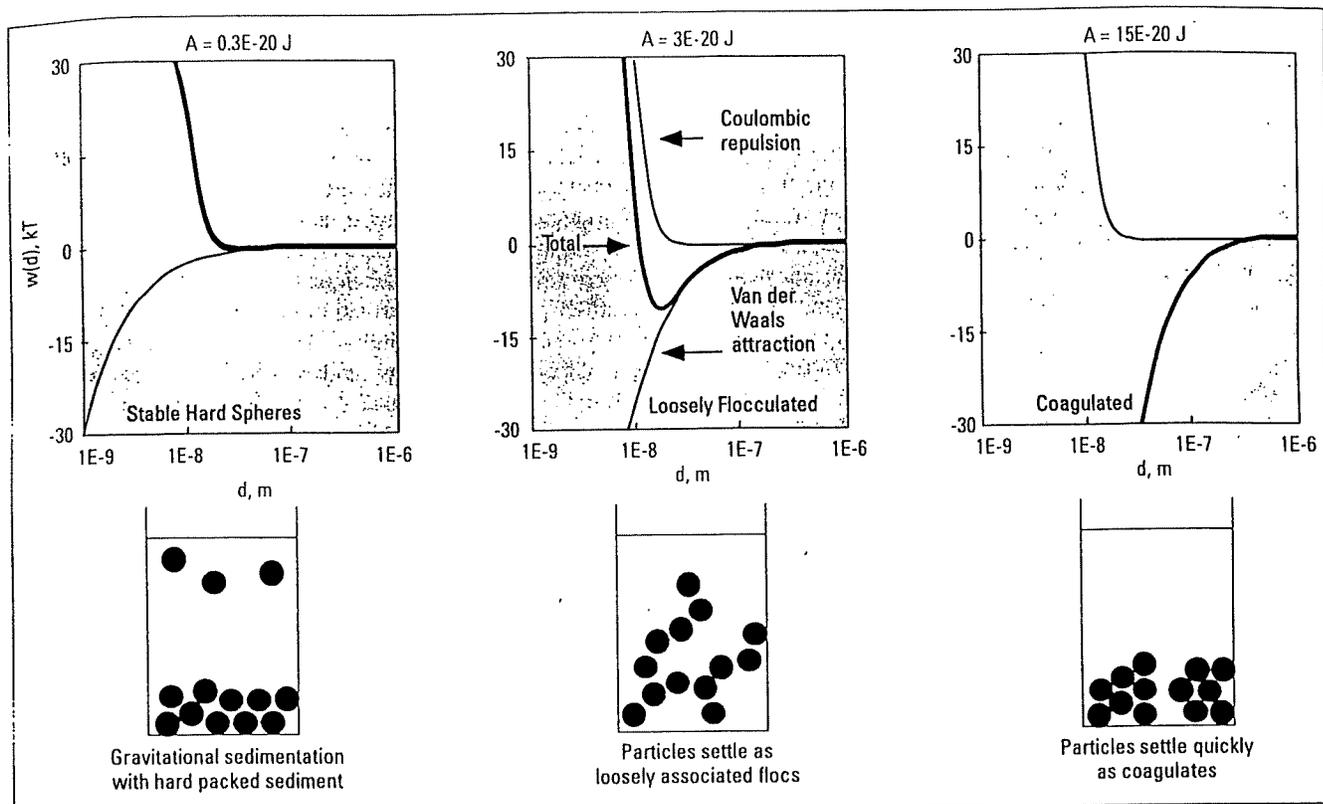
The potential of interaction depends upon interparticle separation  $d$ ;  $1/\kappa$  is the Debye length, which characterizes the thickness of the electric double layer surrounding the particles;  $\rho_{\infty}$  is the ion concentration in the bulk; experimental zeta potential results can be used to estimate surface potential which is held in the  $f(\zeta)$  term; the material properties are encompassed in the Hamaker constant  $A$ . There are also additional effects such as (16): *solvation and structural forces*, for example, some clays and silica dispersions remain stable at salinities where instability normally is expected; *hydrophobic forces*, such as

those associated with rapid coagulation of hydrophobic particles in water, and *ion correlation forces*. Figure 3 shows how colloid stability is defined by the interplay between these effects, particularly with changing Hamaker constant. As a practical example, one can modify surface behavior in an agricultural dispersion through the choice of surfactants to obtain the intermediate case of a loosely flocculated sediment; a farmer could resuspend such a sediment in a pesticide spray tank. The often-chosen alternative, however, is to make a dispersion with high repulsive forces; this eventually leads to a hard packed sediment and an unhappy farmer.

The *wettability* of powders by liquids includes those intermolecular interactions where the particle/air (hydrophobic) interface  $\gamma^{sv}$  must be replaced by a particle/liquid interface,  $\gamma^{sl}$ . Experimentally the interaction between the liquid and the solid, and air is observed in the contact angle  $\theta$  of the liquid on a macroscopic surface, and interpreted through the Young equation:

$$\gamma^{sv} + \gamma^{sl} \cos(\theta) = \gamma^{sl} \quad (2)$$

Wettability is in the first step in the dispersion process. The opposite is flotation, which is economically significant in the separation of ores. In this case, the attachment of particles having hydrophobic surface onto air bubbles enables their separation from hydrophilic particles. *Attachment* of other species to the surface of a powder depends upon the chemical nature of the surface chemical moieties. For example, hydrophilic moieties provide sites for adsorption of moisture from the atmosphere; it is well known that silica surfaces are hydrated completely at most relative humidities. In contrast, one would expect a hydrophobic surface with occasional hydrophilic impurities to have only patches of water on the surface. *Adhesion* between particles is of importance in xerography, powder flowability, ceramic processing, and adhesive films, as discussed below.



■ Figure 3. Stability of aqueous dispersions of  $0.5\mu\text{m}$  particles in 0.01 molar electrolyte with changing Hamaker constant.

Characterization and measurement of these surface phenomena for practical powders is inherently difficult, so commonly used techniques are phenomenological, studying an averaged effect over the entire surface. Contact angle studies have been used since Zisman (17) to empirically estimate critical surface tensions of solids such as polymers. While this technique's application to powders has practical limitations (18), it is useful in estimating contributions due to dispersion forces (19,20,21). Electrokinetic measurements, such as zeta potential, surface charge density, and electrokinetic sonic amplitude, are used to characterize surfaces of particles (22), and provide information about ionizable surface species useful for comparisons of powders, product development, and quality control. Interpretation of the data to fundamentally understand the nature of the surface is difficult, however. Adsorption studies remain a very powerful technique for probing pow-

der surfaces, but often are limited to academic studies purely by their time-consuming nature. Recent techniques such as flow microcalorimetry (23) are proving an effective alternative, where a probe molecule is selected to target surface groups of interest, for instance, hydrophobic, acidic, or basic sites. Monte Carlo simulations are proving informative in understanding adsorption and indeed that surface geometry induces adsorption (24). Fourier Transform Infrared-Attenuated Total Reflectance techniques are used for macroscopic surfaces and are showing potential as effective probes of powder surfaces — particularly for identifying surface groups. The Surface Force Apparatus now is widely used in the study of interactions between macroscopic surfaces at nanometer separations, providing an effective testing technique for theoretical work, such as the modeling of interparticle forces. A major contribution is direct measurement of adhesion between surfaces.

Still, it is only recently that Atomic Force and Scanning Tunneling Microscopy (AFM, STM) have been developed as techniques that actually can study surfaces microscopically. A significant difference in these techniques is that they study microscopic force and topology rather than net effects. These methods will help significantly in the understanding of complex surfaces, such as clays, where the edges and faces have different chemical properties, leading to complex electrokinetic behavior and specialized applications. Finally, while vacuum techniques (such as Electron Spectroscopy for Chemical Analysis) are useful for studying inorganics and metals, practical limitations restrict them from application to hydrophobic, organic particulates such as dyes, and pharmaceuticals.

#### Surface coatings/surfactants

It often is desirable that the surface of particles differ from their interior. The internal attributes, such as phar-

macutical efficacy for a drug, and hiding for a  $\text{TiO}_2$  pigment, are their *raison d'être*. Such chemistries, however, often are not conducive to other desirable behaviors, such as powder flowability, wettability, and dispersion stability — and, so, adding a coating may be desirable. Two facets to be considered are:

1. the surface chemistry, which defines the physicochemical interactions with other particles and surrounding media; and

2. the topography, which influences frictional and mechanical interactions with other particles and surfaces.

Three types of coatings can be considered. The first involves adding a *macroscopic layer* of, say, an inorganic material on to the surface — for instance, a silica layer precipitated onto titanium dioxide. This changes the surface chemistry, morphology, and topography of the surface. When the thickness of the adsorbed layer is large compared with the interparticle separation, then its properties (Hamaker constant) dominate behavior. In contrast, when the thickness is small relative to the separation, then the properties of the particle dominate. Alternatively, the coating may be thin, such as *adsorbed surfactant* layers, which may have molecular dimensions and contribute little topographically. Surfactants, particularly in liquid media, can be extremely effective when correctly selected in modifying surface behavior. Examples include adsorption of surfactants to induce intentional flocculation in wastewater treatment, and to prevent coagulation of ink dispersions. The attachment of these surfactants depends upon a balance between the surface sites and surrounding medium. The third option is the addition of metal in vapor-phase particle formation to induce electrostatic repulsion, thereby minimizing particle aggregation (25,26). Here, the surface concentration of metal atoms is still smaller, in fact significantly *less than monolayer*. These additives, however, are highly effective in mod-

ifying surface behavior to confer desired product attributes.

It is only relatively recently that we are beginning to understand the relationship between particle surface properties, like surface energy, chemistry, topography, and sintering temperatures, and overall powder behavior, such as flow, aggregation of pigments in flames, and dispersion. Improved understanding brings the opportunity for design of additives, surfactant design and rational additive selection that should, in turn, provide commercial opportunities.

### Morphological characteristics

Characterization of the size of a single particle is not trivial (7). Because few particles are spherical, there is a need for specialized dimensions, each of which is appropriate to different applications. For example, a surface-to-volume average diameter appropriately weights fines, whereas the mass median diameter is more biased by coarse particles. Usually, size is measured in the laboratory using techniques such as sieving, microscopy, sedimentation, electrical sensing, and light scattering. Each of these have idiosyncrasies that must be understood for correct interpretation. The key developments are in improvements in light-scattering techniques, and in the use of computerized image processing, which speeds useful interpretation of particle images. Image processing is particularly helpful in interpretation of shape, which can be described through shape indices given by, for instance, Fourier or fractal analysis. Other techniques only describe a spherical equivalent size. With shape and size information, the surface area can be inferred; otherwise, one must resort to gas adsorption measurements or mercury porosimetry, which have the additional ability to quantify internal surface area including pore-size distribution.

Recent advances in particle-characterization equipment now make on-line measurement of process streams possible (27). Examples might

include measuring the viscosity and size distribution of an aqueous dispersion exiting a media mill, or the crystal size and shape distribution in a crystallizer. Furthermore, on-line surface-area or solids-loading measurements now are possible using nuclear magnetic resonance and tomographic techniques. Implementation of on-line analysis into process control loops is vital — and should lead to improved process control, productivity, and quality of final products.

Finally, as already discussed, defects and flaws influence chemical and biological activity (28). Defects can be induced by the introduction of additives, or through mechanical processing, such as through the high pressure in particular grinding techniques. Microcalorimetry can characterize the level of defects in terms of an entropy and enthalpy of processing. For crystals, more elaborate techniques, such as Lauer diffraction, may be employed; this approach also provides the level of internal crystal strain or stress.

### Contact mechanics

Because dense powder behavior is dominated by the nature of interaction of particle contacts, it is critical to understand what controls the contact mechanics of particles. Johnson and coworkers (29) were the first to properly account for the added effect of surface forces. JKR theory defines the diameter  $d$  of the contact spot of elastic particles as seen in Equation 3 where  $W$  is the applied load,  $D$  is the harmonic average of the particle diameters,  $E$  is the modified elastic modulus, and  $\Gamma$  is the interfacial energy of the contact. The first-term of Eq. 3 is the relationship between load and contact diameter. The remaining terms represent the *adhesive* effect of surface energy on increasing the contact diameter.

Equation 3 demonstrates the interaction between adhesion and applied load on a powder. Because of rate effects in applied load, it is difficult to directly measure the equilibrium

$$d^3 = 3 \frac{D'}{E'} \left\{ W + \frac{3}{2} \pi \Gamma D' + \left| 3 \pi \Gamma D' W + \left( \frac{3}{2} \pi \Gamma D' \right)^2 \right|^{1/2} \right\} \quad \mu \propto \left\{ W + \frac{3}{2} \pi \Gamma D' + \left| 3 \pi \Gamma D' W + \left( \frac{3}{2} \pi \Gamma D' \right)^2 \right|^{1/2} \right\}^4$$

■ Equation 3.

interfacial energies by pull-off forces, as would be measured by AFM experiments. Pull-off forces can exceed those expected from surface energy due to hysteresis in the contact. Trying to understand this hysteresis in adhesive forces is currently a fruitful area of research for surface scientists.

Kendall treated the behavior of assemblies using JKR theory (30), with two examples being the friction of powders, and the strength of agglomerates. The friction behavior of a powder often is modeled as:

$$\tau = \mu \sigma + c \quad (4)$$

after Coulomb's law, where  $\tau$  is powder shear stress,  $\mu$  is the coefficient of friction,  $\sigma$  is the applied normal stress, and  $c$  is the powder cohesion, or its shear strength in the absence of any applied normal load. Via Eq. 3, Kendall derived an expression for the friction coefficient for a single particle on a flat (see Equation 5). It indicates that friction in powder assemblies arises from the interaction between particle adhesion and applied normal load, even for smooth particles. Inherent in the Coulomb analysis is that adhesion and friction brought about by the applied load are independent. Kendall's result was unexpected, and it might explain in part the curvature of yield loci exhibited for fine powders with increasing load. Practically, however, Eq. 5 shows that friction should be a decreasing function of load, size, and surface energy. Many of these effects are observed in practice, and further verification — particularly as it relates to modifying particle size and surface properties to improve powder flowability — would be useful. In addition to dense powder flow, frictional interactions during particle collision play a major role in controlling the dissipation of particle momentum in solids-transport prob-

■ Equation 5.

lems; this is currently a major area of research crucial to the future development of rapid granular flow simulations. At the other fundamental extreme, the modern techniques of AFM/STM and the Surface Force Apparatus currently are being employed to better understand the microscopic origins of friction, and the relationship between boundary friction and equilibrium, time-dependent adhesion for molecularly smooth surfaces. Modifying Eqs. 3 and 5 to account for real surfaces that exhibit large-scale roughness, asperities, and surface plasticity is equally important. AFM techniques may be used to characterize topological aspects of a surface. Techniques known as nanoindentation or nanoscratching can characterize surface plasticity (31).

In treating the strength of agglomerates, Kendall combined JKR contact mechanics with the theory of fracture of Griffith (32), who demonstrated that flaws act as points of stress concentration, substantially weakening a material, and that the fracture stress is given by:

$$\sigma_f = K_c / \sqrt{\pi c} \quad (6)$$

where  $K_c$  is fracture toughness and  $c$  is a measure of flaw size or defects. Equation 6 provides a material science basis to understand what controls the strength of an agglomerate, or a particle. In the case of an agglomerate, Kendall found fracture toughness to take the form:

$$K_c = 31 \Phi^4 \Gamma_c^{5/6} \Gamma^{1/6} / \sqrt{D} \quad (7)$$

where  $\Gamma_c$  is the fracture energy, distinct and typically larger than the equilibrium surface energy, and  $\Phi$  is the solid volume fraction of particles. This approach indicates what controls the caking strength of powders. In particular, surface properties, such as hardness or moisture,

are incorporated in the surface energy terms. The general validity of Eqs. 6 and 7 need to be examined, however, for more realistic interactions and random distributions of the contacts and flaws.

Finally, let's consider the subject of particle breakage. When subjected to sufficient load, a particle will either deform, fracture, disintegrate, or erode. The exact mechanism depends on flaw distribution, material properties (including fracture toughness, hardness, elastic moduli, and surface properties), and the types and rate of the applied forces. Combining the appropriate elements of dynamic contact and materials science with a knowledge of particle velocities in processing equipment could prove to be a fruitful area of research — with applications to particle attrition in transport, grinding, and compaction processes. In the case of agglomerates, for example, fracture approaches such as Kendall's have been employed to relate fracture toughness to attrition rate of granules in processing equipment (33). In the processing of advanced materials, it may be necessary to eliminate agglomerates in the production of green bodies because they weaken the final structure. Additionally, fracture properties can be related to the primary surface properties of the constituent particles (Eq. 7), giving an approach to tailor agglomerate properties. Modern techniques of nanoindentation may be employed to determine a single particle's material properties, such as hardness, toughness, or elastic moduli.

**The commonality of unit operations**

Powder technology spans a host of industries that rely strongly on similar powder-processing unit operations. This theme becomes apparent from examining typical texts for different industries, such as chemicals, minerals,

**Table 1. Particle properties important to the unit operations of particle processing.**

Goal	Unit Operation	Major Industries	Involved Phenomena	Related Particle Properties
Particle formation	Crystallization	Bulk chemicals Specialty chemicals Pharmaceuticals Agricultural chemicals Foods	Thermodynamic equilibria Reaction Nucleation Crystal growth Mass transfer	Solubility Supersaturation Surface energy Impurities Activation energy
	Precipitation	Polymers Magnetic and electronic materials Ceramics and catalysts	Agglomeration Breakage Settling Purification Termination	Solid diffusion coefficient Size Density Solids loading
	Aerosol reactors	Pharmaceuticals Carbon black Titania Silicas Ceramics	Reaction Nucleation Condensation Sintering Coagulation Aggregation Agglomeration Atomization Pyrolysis	Surface energy Activation energy Solid diffusion coefficient Size Density Viscosity Solids loading
Size enlargement	Granulation	Minerals Pharmaceuticals Agricultural chemicals Consumer products Food Chemicals Ceramics Plastics	Dynamic wetting Granule growth and consolidation controlled by capillary and viscous lubrication Powder flowability Breakage	Surface tension Viscosity Wettability Flowability Granule toughness Liquid content
	Compaction and tableting	Catalysts	Powder compaction Particle deformation Particle breakage	Size Friction Hardness Elastic moduli Surface energy Particle size Solids loading Surface energy Viscosity of solution phase Strain rate Particle friction
	Extrusion Spray drying		Rheology Mixing Particle-wall friction	
Grinding	Comminution Crushing Attrition	Minerals and ores Ceramics and materials Cement Pharmaceuticals  Agricultural chemicals Pigments  Paints	Stresses (type and rate) Solids loading Mobility of powder: packed, loose, entrained	Fracture toughness Hardness and abrasiveness Elastic moduli Structure and flaw distribution Size Softening and melting temperature
	Dry blending	Minerals Pharmaceuticals Catalysts Plastics Coal	Random and collective behavior: stochastic, chaotic, fractal	Size distribution Shape Density Number Friction Surface energy
	Dispersion in pastes  Dispersion in suspension	Consumer products Food Chemicals Ceramics Magnetic media Textile fibers Paper		
Separation	Classification			Size Density Flowability
	Filtration Centrifugation Flotation			

foods, and pharmaceuticals. Table 1 lists the unit operations broadly encountered, and groups them under the general categories of formation, size enlargement, grinding, mixing, and separation; for each, it also details phenomena involved and related particle properties.

This table illustrates an important point. The basic premise of powder technology is that the macroscopic performance of unit operations is controlled by basic particle properties, and that a better understanding of interparticle interactions can improve the performance of these unit operations, and the resulting quality of the derived product.

Unfortunately, a lack of appreciation of basic particle interactions often leads engineers to conclude that there are no governing principles at hand — and to rely instead almost entirely on empiricism or previous experience. This high degree of empiricism, in turn, has led some academicians to erroneously concur that particle processing is an empirical art, further stifling progress in the field. These misconceptions will be rectified in a forthcoming article that will review the governing principles of these unit operations. In addition, the reader is referred to the cited texts. Table 2 highlights many of the research challenges and possible directions for these unit operations, as well as for the support operations of materials handling and particle characterization.

### **The importance of integrated design**

Let's close our discussion of unit operations by considering the manufacture of a typical particulate product, which easily could involve several plants in different locations. Today's common industrial culture promotes the separate development or suboptimization of each step rather than *integrated* design of the whole entity. While sometimes acceptable, there is a penalty in continuity that becomes increasingly debilitating. For example, increases in product purity in crystallization, or over-grinding in a milling step used for intimate mixing could reduce subsequent granulation yields, due to changes in wetting and flowa-

bility properties, respectively. When more than one company or contractor is involved, each producer-customer relationship increases the magnitude of the disconnect.

Our example begins with the grinding and flotation of a mined ore, with the economic objective of lowering transportation costs to a subsequent processing plant. The ore then must be further purified through a crystallization process ending in a solid/liquid separation, and drying of the crystals. The dried crystals, which are cohesive and difficult to manage, must be wet-granulated. The resultant free-flowing granular product is packaged and sold. The customer disperses it in a liquid. It subsequently is wet-milled with other ingredients to produce a paint, which is formulated to satisfy very specific customer requirements, such as nonsettling behavior and hiding power.

A focus on individual unit operations leads to a diminished understanding of the effect that a set of particle properties controlled by one unit operation may have upon the next; thus, inefficiencies are propagated through the system. The solution is to realize that the role of unit operations is to *engineer* particles with certain properties, not just chemical yield, and to understand what properties are important to the next stage of processing. This state of mind fosters optimization of the entire chain of production as an integral system.

### **Education and research directions**

A recent National Science Foundation (NSF) workshop for the Particle Technology Forum (PTF) reviewed the U.S.' needs for education and research. Unlike, for instance, Germany and Japan, the U.S. offers no formal education in particle technology; courses that cover our current knowledge, even though in some cases phenomenological, should be developed. In addition, we need to bring together interdisciplinary research efforts focused on solving problems in particle technology (see Table 2). Of course, we also must boost awareness of particle

technology among engineers in general. Rather than *ad hoc* efforts, there needs to be a grand design. Organizations such as AIChE and NSF should take a leadership role, but success also will hinge upon governmental, corporate, and university commitment.

**Education needs.** The Education Committee of the American Filtration Society is working on a plan of action to introduce fluid/particle and multiphase processing into engineering programs (35). The PTF is considering possible approaches to introduce powder technology into engineering curricula; it might be most realistic to simply alter the content of current laboratory and lecture courses such as unit operations, plant design, and transport phenomena. In addition, continuing education may play a role. These educational changes will meet an important industrial need for graduating engineers able to practice particle engineering.

**Research needs.** We already have highlighted many of the current research needs and directions. These efforts basically fall into one of three groups. The first deals with trying to characterize particles and their interactions. Examples are the use of SFA/AFM techniques to better understand friction and surface energy, and the development of in-line size analyzers. The second deals with understanding how particle properties translate to bulk behavior, and how we can modify these properties. The last uses this information to *engineer* particles by imparting them with desirable properties, either through the use of chemistry, such as by additives, and through appropriate process-equipment design, such as with mechanochemistry induced by grinding. For real success, interdisciplinary collaboration and a holistic view of the entire manufacturing train, from raw ingredients to the customer, are critical.

### **A particular role for improving competitiveness**

Many of our industries are mature. Therefore, chemical engineers no longer can focus solely on yield, or rely on novel developments for product renewal. We must manufacture products with outstanding end-use

**Table 2. Selected research directions for improved particle processing.**

Goal	Unit Operation	Research and Growth Areas
Particle formation	Crystallization Precipitation Aerosol reactors	Prediction and control of crystal shape Impurity/crystal/solvent interactions Advanced material synthesis (for instance, AlN, and Si <sub>3</sub> N <sub>4</sub> ) Particle formation in reactive turbulent flows Cluster dynamics Transport properties of irregular particles Gas and surface chemistry during aerosol formation Innovative aerosol processes (such as plasma, laser, and spray pyrolysis)
Size enlargement	Granulation  Compaction Tableting  Extrusion  Spray drying	Physical-based kernels for scale-up and control Particle velocities and mixing patterns Microwave heating and drying Melt granulation Combined operations (for example, granulation, drying, and coating) Modularity and cleanout Relating compaction processes to particle properties Minimization of agglomeration and flaws Increased understanding of stress transmission and effect of flaws Effects of size, shape, and particle interactions on rheology Wall interactions and shear-induced particle diffusion and mixing Modeling of drop formation and solidification
Grinding	Comminution Crushing Attrition	Increased energy efficiency of size reduction and energy scale-up Prediction of liberation of phases, size distributions, and particle shape Internal wear and contamination Translating particle properties to single- and multiple-particle breakage Grindability testing of small samples High-pressure-roller and high-G mills Mechanochemistry and routes to new materials
Mixing	Dry blending  Dispersion  Dispersion	In-situ sensors and analyzers Continuous mixers Orders and partially ordered mixtures Nonideal mixtures with density and size distributions Stochastic, chaotic, percolation, and fractal modeling Statistical mechanics and molecular dynamics Time-series analysis of nonlinear systems Scale-up and process synthesis On-line probes that can extract structure, stress, in pastes and kinematics Effects of size, shape, and particle interactions on rheology Effects of surfactant and surface structure in suspension on force interactions (SFA, AFM) Molecular engineering of L-B films Effect of polymer conformation on particle interactions Decomposition and recycling of dispersants and flocculants Influence of radioactivity and biologicals on particle interactions
Separation	Classification Filtration Centrifugation Flotation	
Materials handling		Constitutive modeling of powder flow Finite-difference and granular-flow modeling of bins Prediction of static/dynamic bin structural loads Handling of fine powders and nanomaterials Prediction of erosion and attrition Particle/particle interactions and electrostatics Increased pressure effects Reliable flowmetering Realistic simulations and experimental verification of solids transport
Particle characterization		In-line measurements, particularly for highly concentrated systems Acoustic measurements Tomographic techniques In-line image analysis and pattern recognition Incorporation of measurements in process-control models

behavior for the customer. In many cases, this means paying more attention to particles. We have reviewed the relationships that exist between fundamental physics, mechanical and physicochemical particle properties, and powder behavior in unit operations and product performance. It is vital that we are able to engineer particle properties, preferably in the formation stage, if we wish to control the quality of particulate products and remain competitive. We either can resort to empiricism and art, or we can turn to the principles outlined in this article. Using these principles of powder behavior, rooted in our understanding of particle properties, to modify processes and products is the very definition of powder technology.

Government attempts to direct research to boost competitiveness must go beyond some of the recent *fix-it* initiatives of the current administration on advanced materials, the environment, manufacturing competitiveness, and biotechnology. They must not overemphasize the new and novel at the expense of core competencies.

Are the problems faced in the production of modern ceramic parts altogether different from those faced by the ancient potter of Egypt? Critical in the formation of ceramics is the elimination of strength-weakening flaws that can be introduced by particle interactions such as agglomeration; producing nanoparticles by novel routes will not remove this problem. Powder processing and the underlying governing phenomena are not new. The principles of powder mechanics have been well established for 40 years, yet we continue to ignore them in the design of hoppers, undermining manufacturing productivity. We are very good at discovering active ingredients for pharmaceuticals and agricultural chemicals, but biological efficacy often is controlled by the rate-limiting physicochemical structure of the particle. Lost drug activity or environmental concerns, such as groundwater contamination, frequently result.

What is needed, first and foremost, is an increased awareness of the importance of powder technology, not only to

## Acknowledgment

The research areas highlighted in Tables 1 and 2 were developed from contributions by A. Myerson, S. Pratsinis, A. Weimer, P. Stone, K. Sastry, D. Fuerstenau, L.-T. Fan, B. Moudgil, J. Carson, G. Klinzing, J. Sinclair, O. Walton, G. Fuller, and T. Allen at a recent NSF workshop.

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**B. J. ENNIS** is chair of the agglomeration and size enlargement subgroup of the Particle Technology Forum, and vice chair of section 3A — powder technology of AIChE's Programming Committee. He received a BS from Rensselaer Polytechnic Institute, and a PhD from City College of New York, both in chemical engineering.

**J. GREEN** holds an MS from the University of Bristol (U.K.), and a PhD from Carnegie Mellon University, both in colloid and surface science.

They work for DuPont Agricultural Products, Wilmington, DE (Fax: 302/695-7804), and focus on solving commercial particle problems through an understanding of intermolecular and physicochemical principles. Their research interests include granulation, powder mechanics, on-line characterization and control, paste rheology, wetting dynamics, adsorption phenomena, surfactancy, surface characterization, and dispersion stability.

**R. DAVIES** is the principal consultant and manager of the Center for Particle Science & Technology, an interdisciplinary group within DuPont, Wilmington, DE (Fax: 302/695-2504) that deals with particle processing issues. He chairs the technical committee of Particle Technology Forum, and also is well known for his previous role as technical chair of the International Fine Particle Research Institute. He earned a PhD in physics from Loughborough (U.K.) University of Technology.

manufacturing, but also to areas such as biology, the environment, and materials. This awareness now exists in countries such as Germany and Japan. Although some researchers and practitioners here already recognize this importance, we must get senior management, government officials, and university administrators to appreciate the unique problems associated with powder processing before we can achieve a real driving

force to their solution. With their mandate, we can effectively direct research and education efforts towards increasing our understanding of how particle properties translate to bulk behavior and mastering our ability to tailor these properties to a given beneficial end-use.

CEP

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# Higher Education in Germany

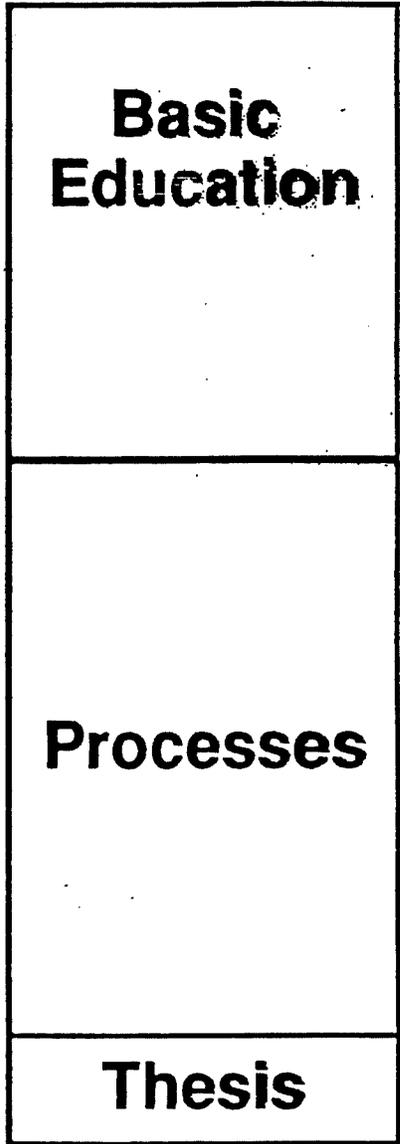
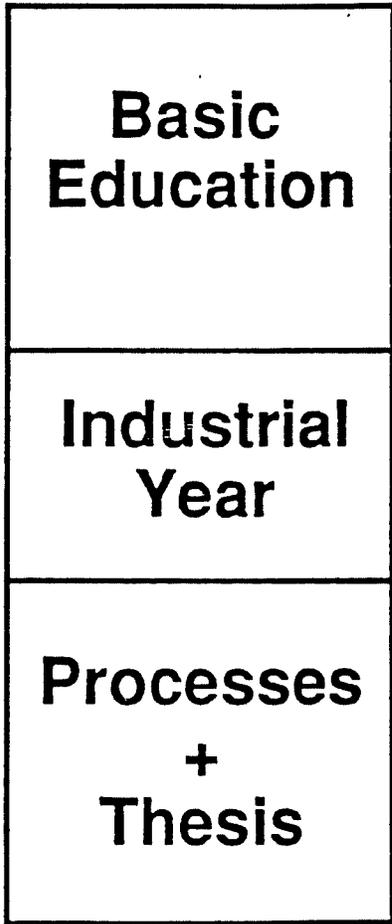
APPENDIX I

**Highschool Graduate**

**College**

**University**

0  
1  
2  
3  
4  
5  
↓  
years



**Dipl.-Ing. (FH)**

**Dipl.-Ing.**

## Particle Technology

<b>1</b>	<b>Fundamentals (all unit operations, PSA)</b>	<b>4</b>	<b>2</b>	<b>14</b>
<b>2</b>	<b>Multiphase Flow</b>	<b>2</b>	<b>1</b>	<b>14</b>
<b>3</b>	<b>Gas Cleaning (PSA, Filtration, Wet Scr. Electrostatic Precipitators)</b>	<b>2</b>	<b>1</b>	<b>14</b>
<b>4</b>	<b>Solid-Liquid Separation (Sedimentation, Filtration)</b>	<b>2</b>	<b>1</b>	<b>14</b>
<b>5</b>	<b>Classification in Gases</b>	<b>2</b>	<b>1</b>	<b>14</b>
<b>6</b>	<b>Mixing (Powders and Pastes)</b>	<b>2</b>	<b>1</b>	<b>14</b>
<b>7</b>	<b>Powder Flow, Design of Hoppers and Bins</b>	<b>2</b>	<b>1</b>	<b>14</b>
<b>8</b>	<b>Particle Characterization</b>	<b>2</b>	<b>1</b>	<b>14</b>
<b>9</b>	<b>Part. Technolofy Seminar</b>	<b>2</b>		
<b>10</b>	<b>Fundamental Laboratory Work</b>		<b>4</b>	<b>14</b>
<b>11</b>	<b>Laboratory Work (Processes, Environmental Technology, PSA,.....)</b>		<b>6</b>	<b>14</b>
<b>12</b>	<b>1.Thesis</b>			<b>(3 month)</b>
<b>13</b>	<b>Diplom Thesis</b>			<b>(4 month)</b>

# Particle Technology, Fundamentals I

## 1 particulate systems

## 2 characterization of Particles

particle characteristics, shape description, shape factors, equivalent diameters

## 3 evaluation of particle size analysis data

representation of distributions, approximation functions, moments, average particle sizes, surface area

## 4 sedimentation

stationary settling rate, movement of single particles in a stationary fluid, settling in a gravity and a centrifugal field, settling rate at higher Reynolds numbers, influence of particle size (Brownian motion, Cunningham correction), influence of solids concentration, convection currents, technical examples

## 5 flow through packed beds

d'Arcy equation, Carman-Kozeny equation, filter equation, filter experiment, technical filtration examples

## 6 mixing

characterization of mixing, sample size, technical examples of mixers

## 7 comminution

physical fundamentals, stress mechanisms, crushing of single particles, different types of comminution principles

## 8 size enlargement

strength of agglomerates, granulation techniques

## **Particle Technology, Fundamentals II**

### **1 movement of single particles in a flow**

force balances, flow fields, drag laws, equations of motion, calculation of particle trajectories

### **2 characterization of a classification**

mass balances, density distributions, grade efficiency curves, cut sizes, sharpness of cut

### **3 classification of particles in gases**

basic principles, flow fields, secondary flow, different types of classifiers

### **4 cyclone separators**

principle, flow fields, basic theories for the precalculation of cut size and pressure drop

### **5 pneumatic conveying**

force and momentum balances, pressure drop in vertical and horizontal ducts, influence of solids concentration

# Particle Technology, Gas Cleaning

## **1 introduction to gas cleaning**

**gaseous, liquid and solid air pollutions, environmental laws**

## **2 sampling techniques**

**sampling from flowing gases, deposition measurements of particles from ambient air, fundamentals of aspirating probes, classifying and non-classifying particle separation from flowing gases**

## **3 aerosol measuring techniques**

## **4 wet scrubbers**

**principle of wet scrubbing, droplet production, theoretical cleaning efficiency of droplets, wet scrubbers principles and design, precalculation of a model wet scrubber**

## **5 gas cleaning by filtration**

**deposition of particles on filter fibres, pressure drop of a layer fibres, the Deutsch'equation, principle, precalculation and design of bag filters, filter media**

## **6 electrostatic precipitators**

**principle, precalculation and design of electrostatic precipitators, grade efficiency**

# **Particle Technology, Characterization**

## **1 introduction to particle characterization**

## **2 characterization of single particles**

particle characteristics, equivalent diameters, shape description, shape factors

## **3 measurement of solids density**

liquid and gas pycnometers

## **4 sampling and sample splitting**

sampling and sample splitting of powders, aerosols and suspensions

## **5 determination of size distributions from single particles**

indirect counting methods, microscope, automatic and semi-automatic image analysis, direct counting methods, sensing zone methods, light scattering and extinction methods, diffraction pattern analysis, other methods

## **6 sieve analysis**

## **7 on-line analysis**

## **8 determination of surface area**

permeability methods, photometrical methods, sorption methods

# Particle Technology, Mixing

## 1 introduction

principle, aim of mixing, mathematical description of mixing quality, time dependency of mixing

## 2 mixing of liquids-stirring

types of stirrers, power consumption and mixing time, rheological behaviour of liquid substances, turbulent structure in mixed fluids

## 3 mixing using free turbulence

## 4 mixing in tubes, use of static mixers

## 5 mixing of viscous media

kneaders, extruders, precalculation of volume flow rate and power consumption with single shaft extruders

## 6 mixing of powders

mixers with moving parts, pneumatic mixers, methods of powder flow, mixing time and power consumption

# Particle Technology, Solid-Liquid Separation

## 1 introduction to solid-liquid separation

## 2 sedimentation

sedimentation in a gravity or centrifugal field, thickeners, classifiers, centrifuges (decanter, separator)

## 3 residual moisture

Laplace and Young's equation, capillary pressure, capillary rise, liquid contents after mechanical dewatering

## 4 flow through packed beds, filtration theory

structures of filter cakes, mass balances differential equation of flow through packed and solutions, optimum operating conditions

## 5 principle and design of filters and filter centrifuges

filter media, filter aids, different types of filters (sand filter, filter presses, Kelly Filter, Sweetland filter, candle filters, drum filters, disc filters, belt filters) different types of filter centrifuges

**IMPACT**  
**of the field**  
**PARTICLE FORMATION IN GASES**  
**on**  
**PARTICLE TECHNOLOGY**  
**as practiced in industry**

by

Sotiris E. Pratsinis  
Department of Chemical Engineering  
Center for Aerosol Processes  
University of Cincinnati

Paul D. Stone and Alan W. Weimer  
Ceramics & Advanced Materials Research  
Dow Chemical U.S.A.

June 25-26, 1993  
Washington, D.C.

# **INDUSTRIES & PRODUCTS**

## **SPRAY-DRIED POWDERS**

Coffee, Milk, Detergents

## **PHARMACEUTICAL**

Controlled Drug Delivery (inhalers, protein medicine)

## **COATINGS**

Films & Sprays

## **CARBON BLACKS**

Tires, Inks, Reinforcement for Plastics

## **TITANIA**

Paints, Catalysts, Semiconductors

## **FUMED SILICA**

Optical Fibers, Filler, Toothpastes, Coatings

## **CERAMICS**

Superconductors, AlN, SiC, B<sub>4</sub>C, Titanates

## **INCINERATION OF HAZARDOUS WASTES**

Suppression of Toxic Particle Formation/Release

# LINKAGES WITH INDUSTRY & PROFESSIONAL SOCIETIES

## INDUSTRIES

Dow  
DuPont  
AT&T  
Corning Glass  
ALCOA  
Texas Instruments  
Procter & Gamble  
General Electric

## PROFESSIONAL SOCIETIES

AICHE  
ASME  
MRS  
Amer. Assoc. Aerosol Res.  
Filtration Soc.  
American Ceramics Soc.  
Fine Particle Soc.  
ISA

# **INTERACTION WITH PARTICLE TECHNOLOGY FORUM SUB-GROUPS**

**Solids Transport & Handling  
Particle Characterization  
Fluidization & Multi-Phase Flow  
Solids Transport & Handling  
Powder Mechanics & Solids Flow  
Agglomeration & Interparticle Forces**

**ENVISION CO-SPONSORED SESSIONS AT PROFESSIONAL MEETINGS  
& CO-EDITED SYMPOSIA**

# ORGANIZATION OF FUNDED RESEARCH PROJECTS

## CROSS-FUNCTIONAL PROJECTS SHOULD HAVE MULTIPLE PI'S

(e.g. Powder synthesis projects should be guided by synthesis investigators (probably chemical/mechanical engineers) as well as characterization & evaluation investigators (probably ceramics/materials engineers) in order to insure that evaluation of the powder is properly included as part of the overall program.

## **EDUCATION**

UNFORTUNATELY, NO FORMAL EDUCATION PROGRAM EXISTS & POWDER TECHNOLOGY IS ONLY STUDIED IN A RATHER FRAGMENTED FASHION AT U.S. INSTITUTIONS (RELATED M.S. & Ph.D. THESES)

### **NEEDS:**

- CLOSER MATCH OF FUNDED GRANTS WITH INDUSTRIAL NEEDS
- ENCOURAGEMENT OF INDUSTRIAL/ACADEMIC COMMUNICATION INCLUDING FACULTY SABBATICAL LEAVES AT INDUSTRY & VICE VERSA & STUDENT RESEARCH TIME AT THE INDUSTRIAL SPONSOR'S LOCATION

# **ROLE/SIGNIFICANCE OF PARTICLE FORMATION IN GASES ON US COMPETITIVENESS**

**[MATERIALS SYNTHESIS IS LINING UP AS A TECHNOLOGY AREA  
OF INTENSE GLOBAL COMPETITION (e.g. AlN, Si<sub>3</sub>N<sub>4</sub>)]**

**METHOD OF PROJECT FUNDING/SELECTION SHOULD ENCOURAGE U.S.  
INDUSTRIAL PARTICIPATION TO HELP INSURE THAT PROJECT AREAS  
ARE OF PRACTICAL SIGNIFICANCE. THIS PARTICIPATION SHOULD  
INCLUDE INTELLECTUAL PARTICIPATION AS WELL AS MONETARY  
SUPPORT.**

**US INDUSTRIAL PARTICIPATION CAN BE ENCOURAGED BY PROPER  
ASSIGNMENT OF INTELLECTUAL PROPERTY RIGHTS**

# **RECOMMENDED RESEARCH TOPICS**

**FUNDAMENTALS OF PARTICLE FORMATION IN REACTIVE  
TURBULENT FLOWS**

**MEASUREMENT OF FUNDAMENTAL PROPERTIES, INCLUDING  
INSTRUMENTATION DEVELOPMENT**

**Cluster Dynamics**

**Compare Experiments with Theory**

**Develop Control Loops for Industrial Production**

**TRANSPORT PROPERTIES OF IRREGULAR PARTICLES**

**GAS & SURFACE CHEMISTRY DURING AEROSOL FORMATION**

**INNOVATIVE AEROSOL PROCESSES**

**Thermal Reactors**

**Plasma Reactors**

**Laser Reactors**

**Flame Reactors**

**Spray Pyrolysis/Drying**

## SUGGESTED "FUNDED PROJECT" FORMAT

- Cross-functional funded research projects is a goal.
- Funding from NSF, or federal agencies.
- Any funded project (or specified %) would have to be a partnership between university and one, or more, industrial partners. Perhaps the industrial partner should cost share (dollars, personnel, equipment.)
- This mechanism is being used in many government programs, e.g. ARPA.
- It addresses many of our concerns.

## APPENDIX F

### CRYSTALLIZATION AND PRECIPITATION

Allan S. Myerson  
Department of Chemical Engineering  
Polytechnic University  
Six Metrotech Center  
Brooklyn, New York 11201

Key Research Area and Needs

Crystal Shape - Prediction and Control

Impurity - Crystal Interaction

Management and Control in Industrial Process

Education of Students in Field

Poor - Barely discussed it at all

# COMMINUTION: Introduction

## APPENDIX G

The comminution or size reduction of materials is central to the treatment of ores by physical processing or hydrometallurgical extraction technologies and to the preparation of fine particles for subsequent utilization, such as cement, pulverized coal, and ceramic powders.

**Challenges in comminution are two-fold:**

- 1) To increase the energy efficiency of size reduction processes
- 2) To achieve better control over liberation, size distributions, and particle shape

Low efficiency and lack of product control have far-reaching implications for resource conservation, downstream operations, product optimization, and environmental damage.

## **Why Grinding?**

---

- To **decrease the particle size** or **increase the surface area** of solid materials for further downstream use or processing.

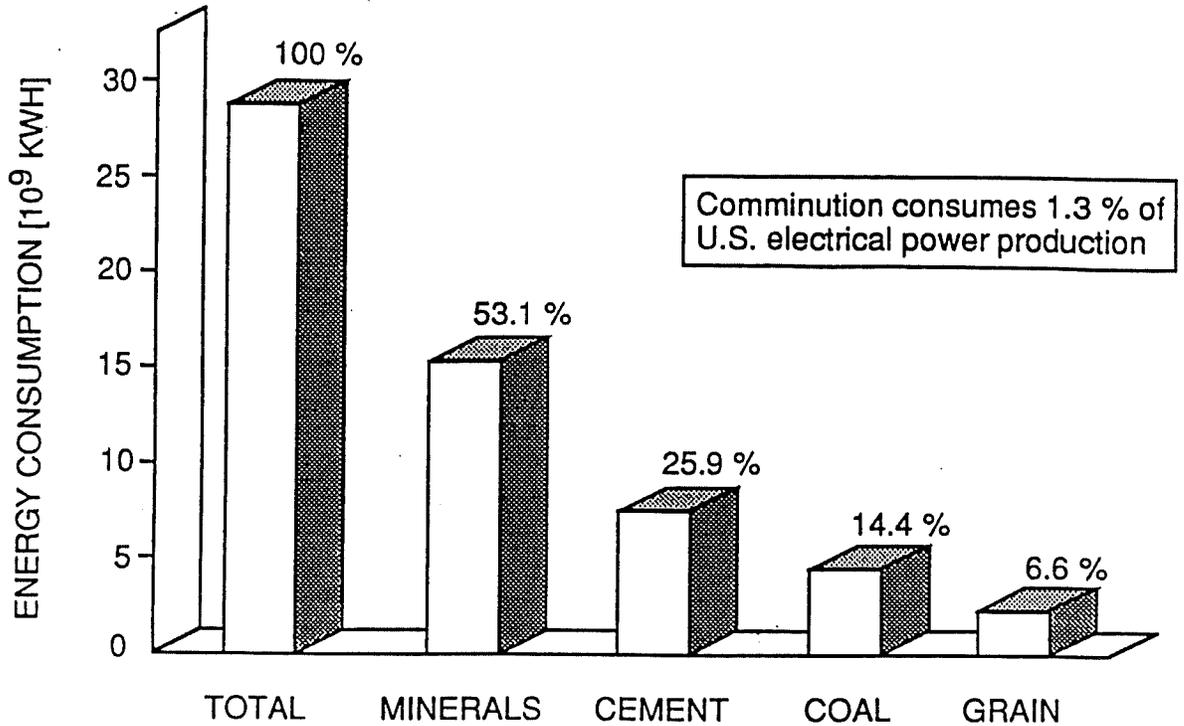
Examples: - Grinding of mineral raw materials for making cement, refractories and ceramics  
- pulverization of food grains  
- fine-grinding of minerals and pigments

- To **liberate useful minerals** from gangue matrix in ores for their subsequent separation

Examples: - Grinding of copper, zinc and lead ores and taconite

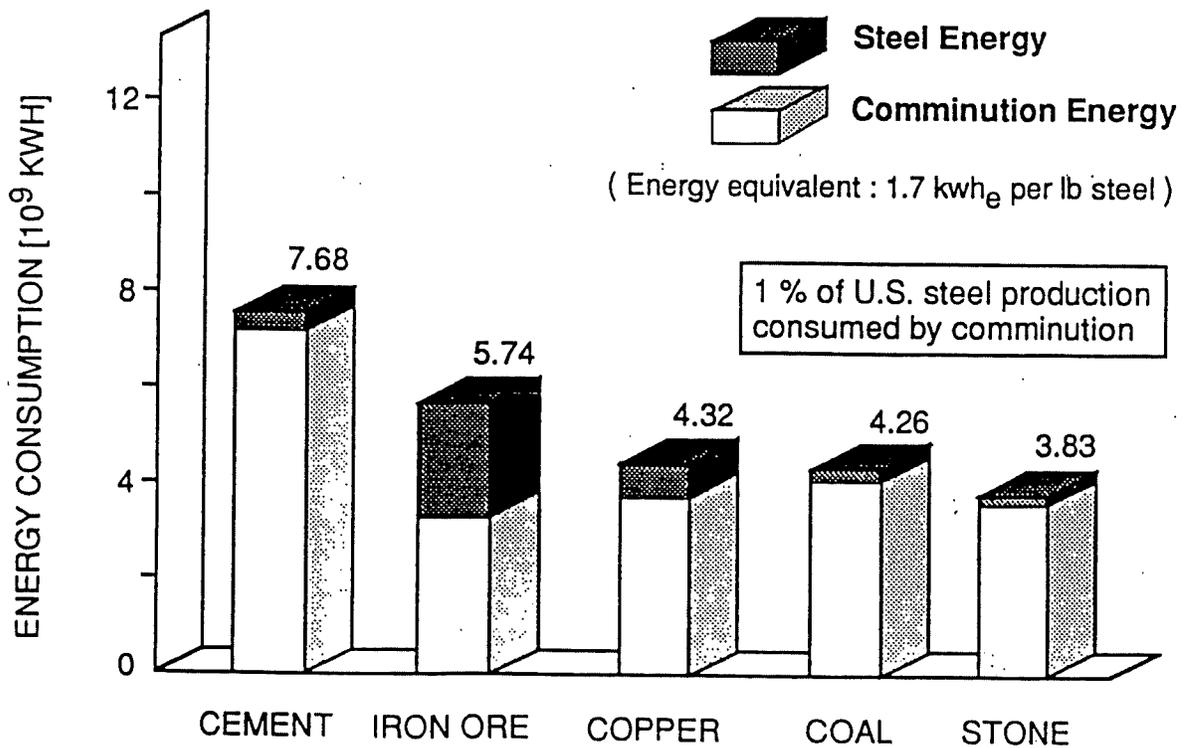
### COMMINUTION AND ENERGY CONSUMPTION

Pub. NMAB - 364 (1981)



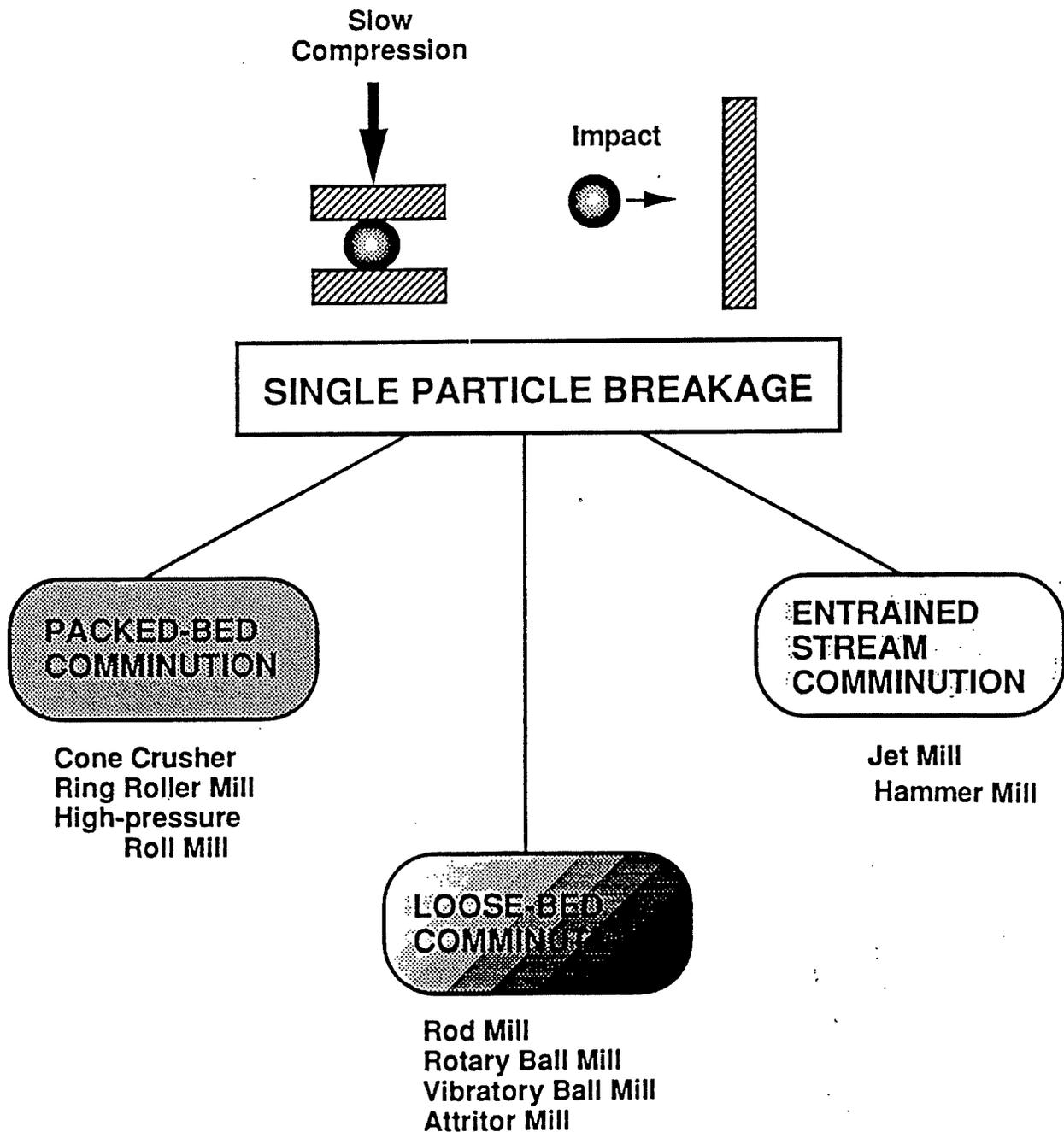
### STEEL AND ENERGY CONSUMPTION IN COMMINUTION

Pub. NMAB - 364 (1981)



# A TWO-WAY CLASSIFICATION OF GRINDING PROCESSES

- by the nature of the stress(es)
- by the mobility of the particulate mass



## ENERGY SINKS IN COMMINUTION

Energy Transfer :                      SP > PB > BM  
Direct                      →                      Indirect

Particles Interaction :                      PB > BM > SP

Metal Wear :                      BM > PB > SP

Breakage Probability :                      SP > PB > BM  
Certain                      →                      Gok

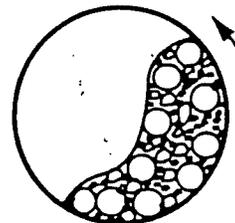
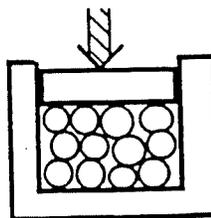
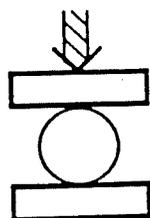
≡

Energy Efficiency :                      SP > PB > BM  
1                      : 1.5 - 3                      : 3 - 10

[ e.g. cement ( J/m<sup>2</sup> )                      30-60                      150-250                      350-500 ]

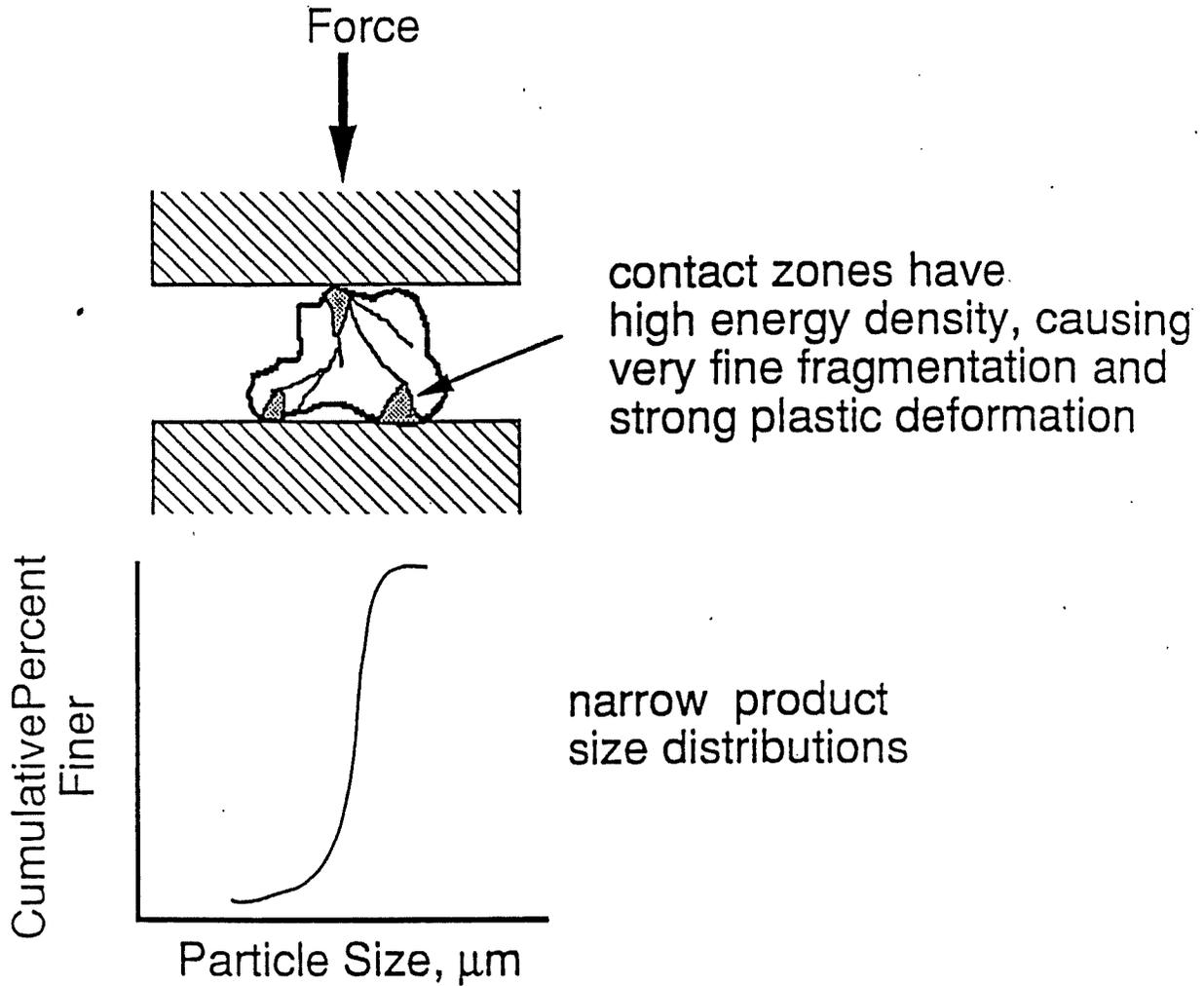
COMMINUTION  
METHOD

{ SP : Single Particle  
PB : Particle Bed  
BM : Ball Mill



# Single-Particle Comminution

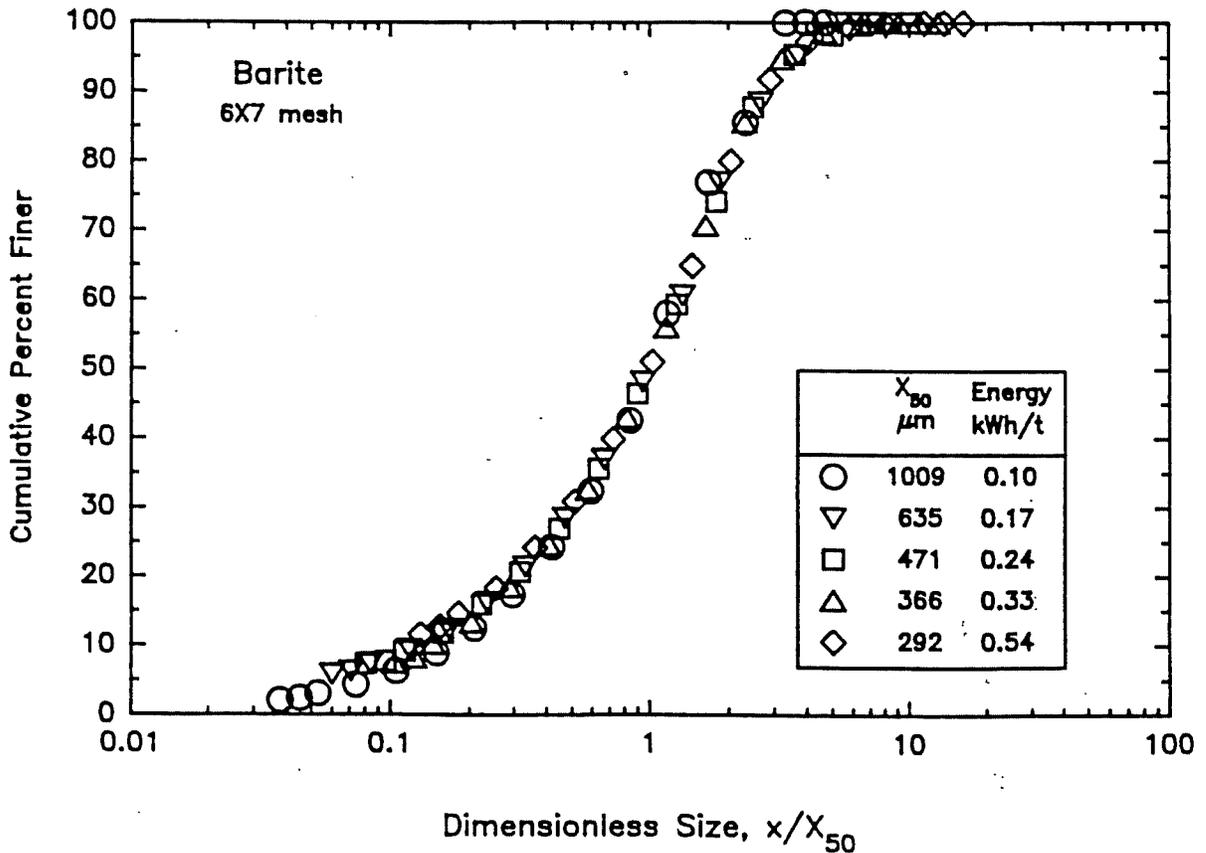
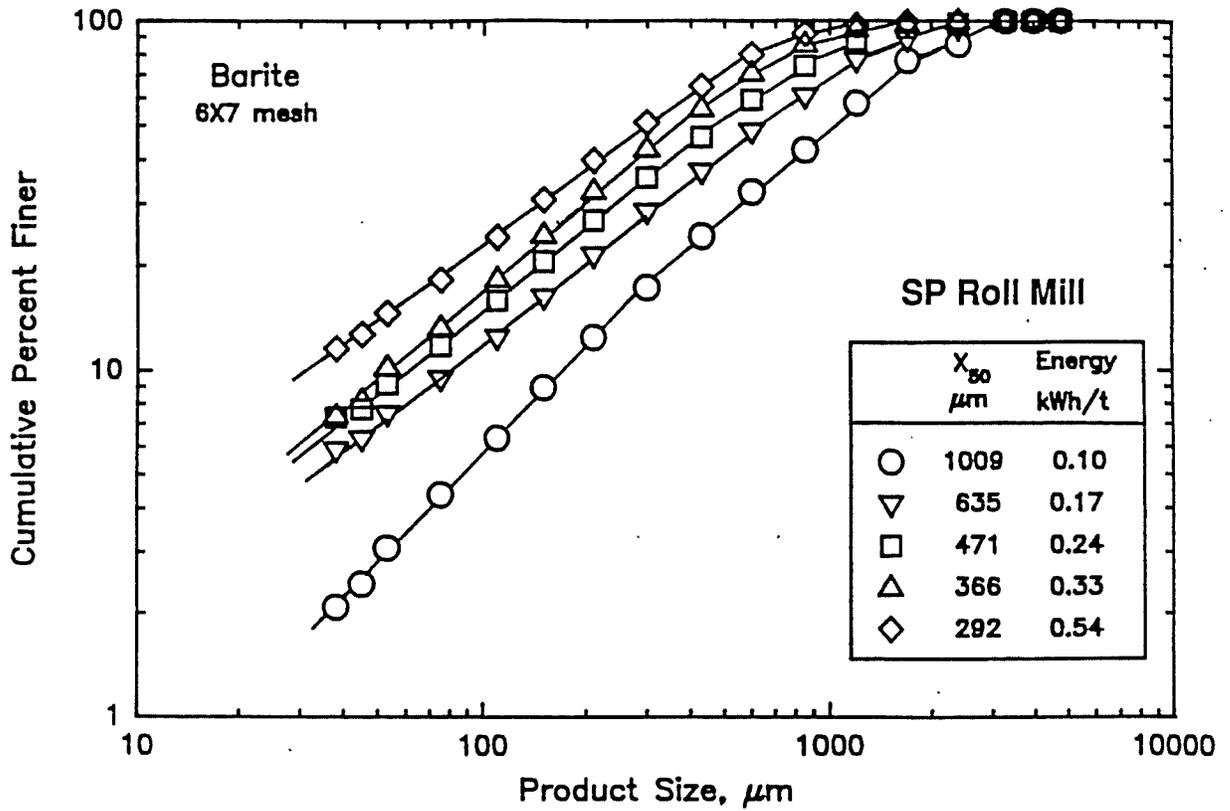
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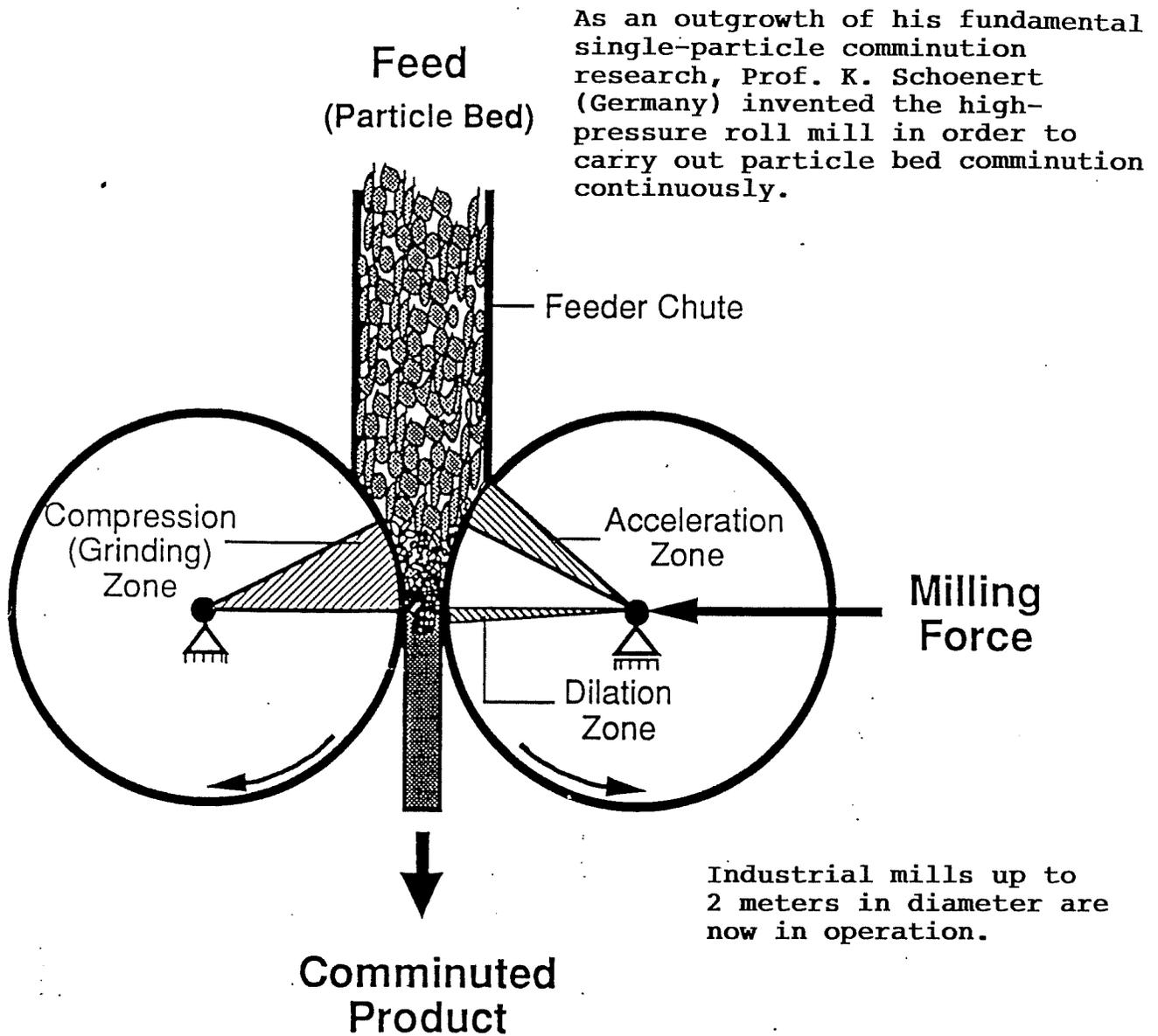
- energy is directly transmitted to the particle
- most energy-efficient mode of particle breakage
- very low throughputs

Single particle breakage measurements provide the baseline for assessing the energy required for comminuting a given material.

# SELF-SIMILAR AND SELF-PRESERVING SIZE DISTRIBUTIONS OF COMMINUTED MATERIALS

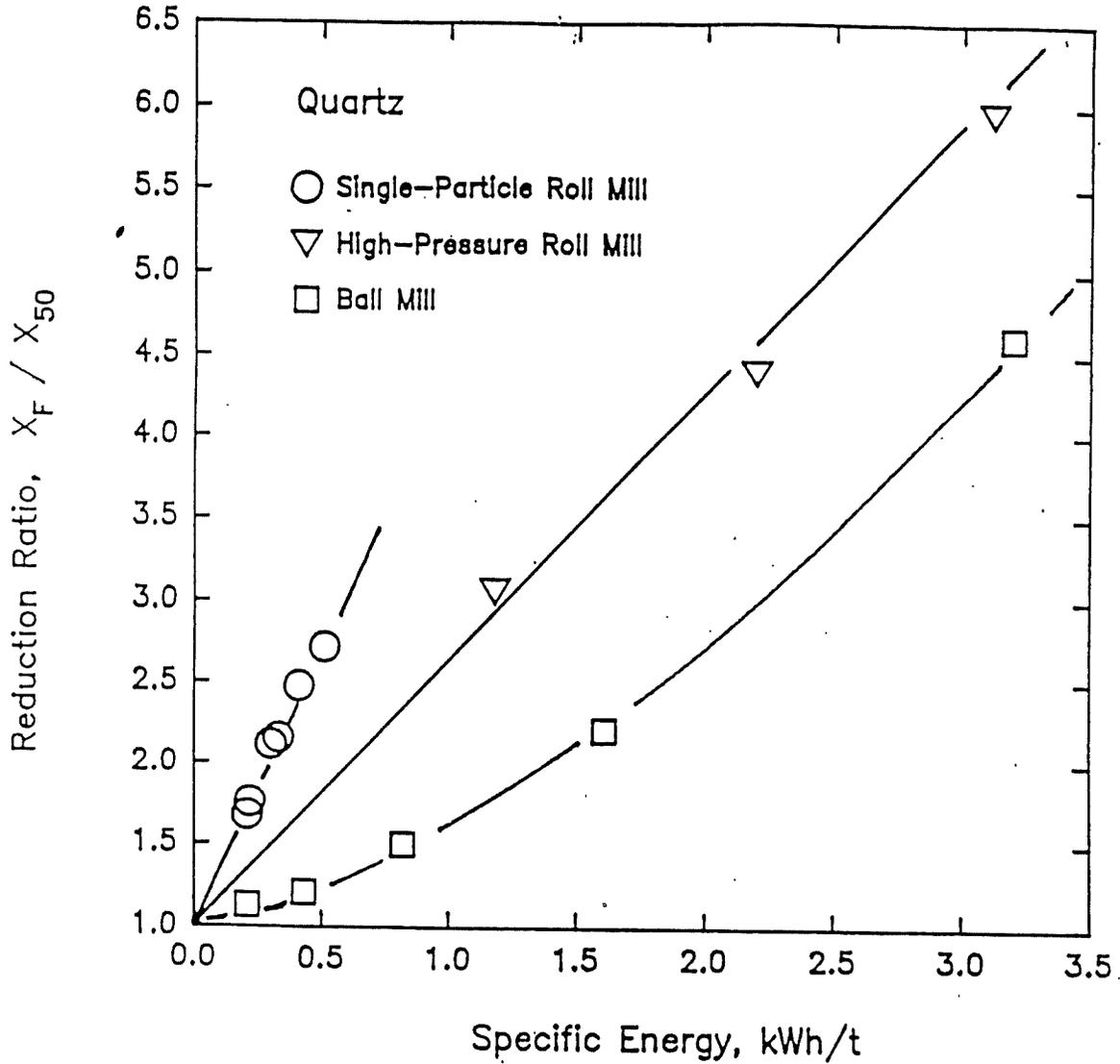


# PRINCIPLE OF HIGH-PRESSURE ROLL MILL COMMINATION



- less efficient than single-particle comminution but 20-40 % energy savings over traditional grinding mills

COMPARISON OF THE ENERGY EFFICIENCY OF THE THREE GRINDING MODES:



$\text{Eff.} = \frac{X_F / X_{50}}{E_m} = \frac{2.5}{E_m}$	Efficiency t/kWh	Relative Efficiency
Single Particle Roll Mill	6.25	1
High Pressure Roll Mill	2.94	0.47
Ball Mill	1.39	0.22

$X_F$  is the mean size of the feed particles and  $X_{50}$  is the mean size of the product particles. The ratio  $X_F / X_{50}$  can be used as a measure of the extent of size reduction.

# SELF-SIMILAR AND SELF-PRESERVING SIZE DISTRIBUTIONS OF FINELY COMMINUTED PARTICLES (after Venkataraman)

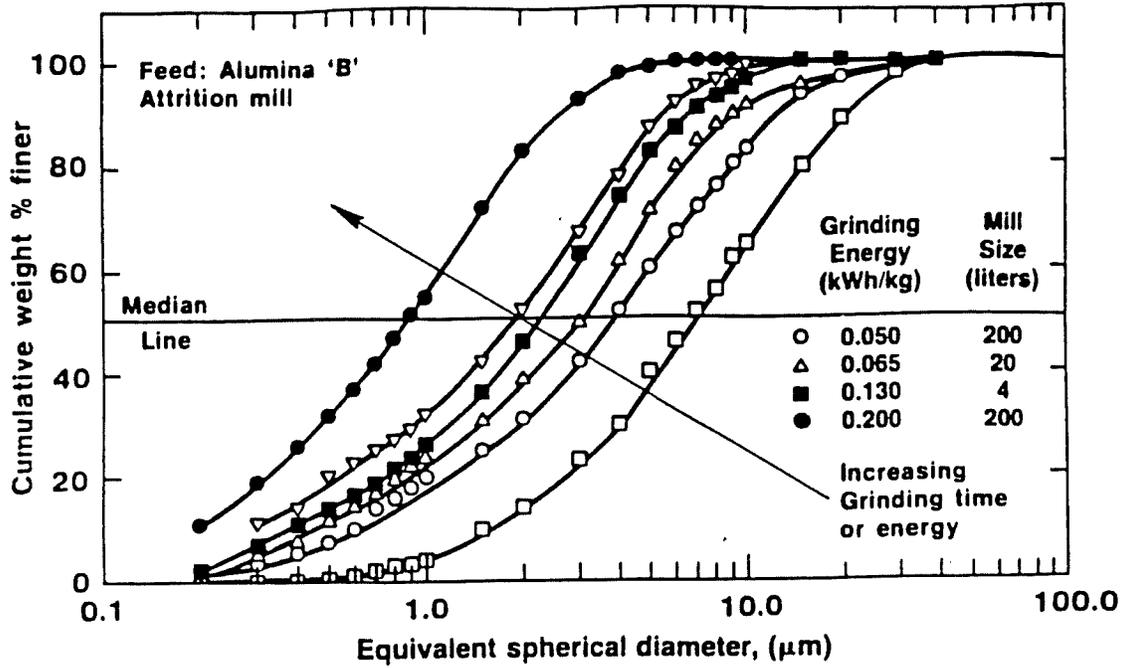


Fig. 2. The dimensional particle size distributions of attrition-ground alumina B.

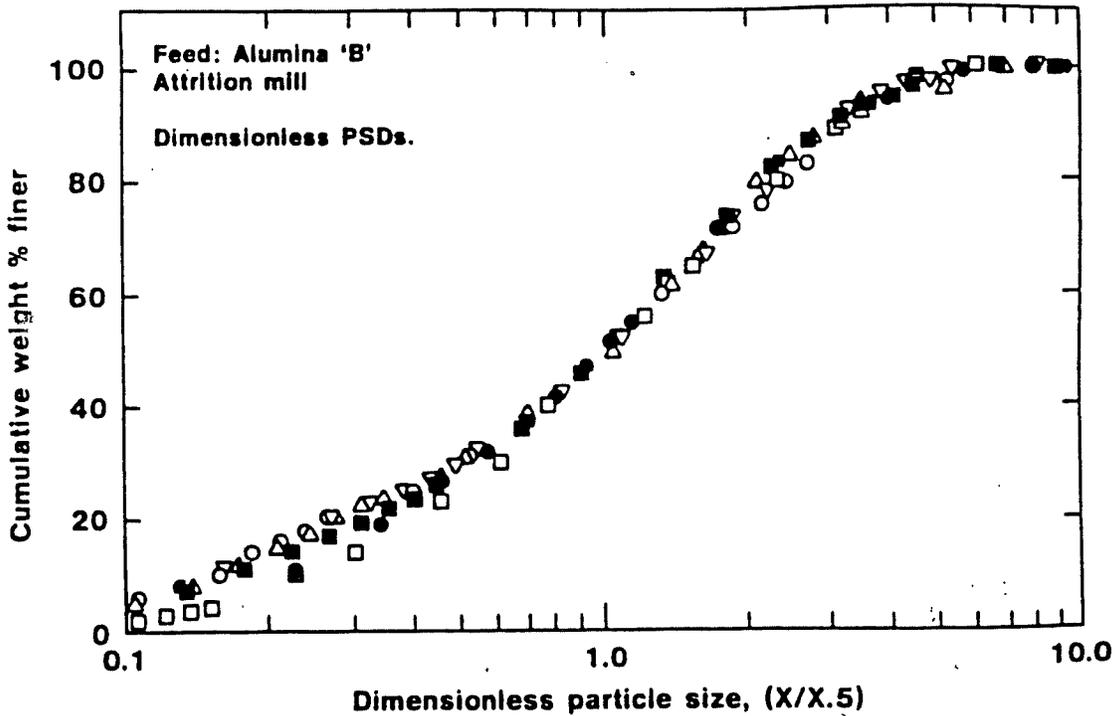


Fig. 4. The nondimensionalized self-similar particle size distribution curve obtained for the data in Fig. 2.

## RESEARCH NEEDS IN COMMINUTION

Because of the high consumption of energy in comminution and the need for tailoring the properties of comminuted particulate materials to applications, research is needed in a number of areas:

- Single and multiple particle fracture in comminution
- Grindability (breakage) testing of small samples
- Interaction of breakage device and material fracture characteristics
- New energy-efficient comminution technology; alternative energy sources
- Modeling and simulation (better dynamic modeling, entire plant simulation)
- Scale-up of comminution devices (predicting power draw of machines, how to supply energy for comminution and to scale it up)
- Fine grinding technology (for improved energy efficiency, control of target size distributions)
- Prediction of liberation
- Process control of comminution systems (instrumentation for liberation, particle shape, etc.)
- Comminution of materials for specific applications
- Interaction with other areas of particle technology (rheology, packing, etc.)
- Classification for fine grinding
- Wear of materials of construction in comminution devices

## Particle Characterisation

- What are the key elements of the topic?
- What Industries are key users
  - key groups in USA, vendors?
- How industrially linked is it?
- Are Domestic and Global links in place? or needed?
- How would Particle Characterization Groups interact in Powder Technology Forum?
- Student Education in Characterization Penn State, Berkely. Where else?
- Research needs? On line?

PARSAT

# PARTICLE CHARACTERIZATION

## Single Particle System

Size  
Particle Size Distribution  
Shape  
Shape Distribution  
Surface Area  
Pore Size  
Pore Size Distribution  
Concentration  
Hardness  
Strength

## Bulk Systems

Surface Chemistry  
Bulk Chemistry  
Magnetic Properties  
Electrostatic Properties

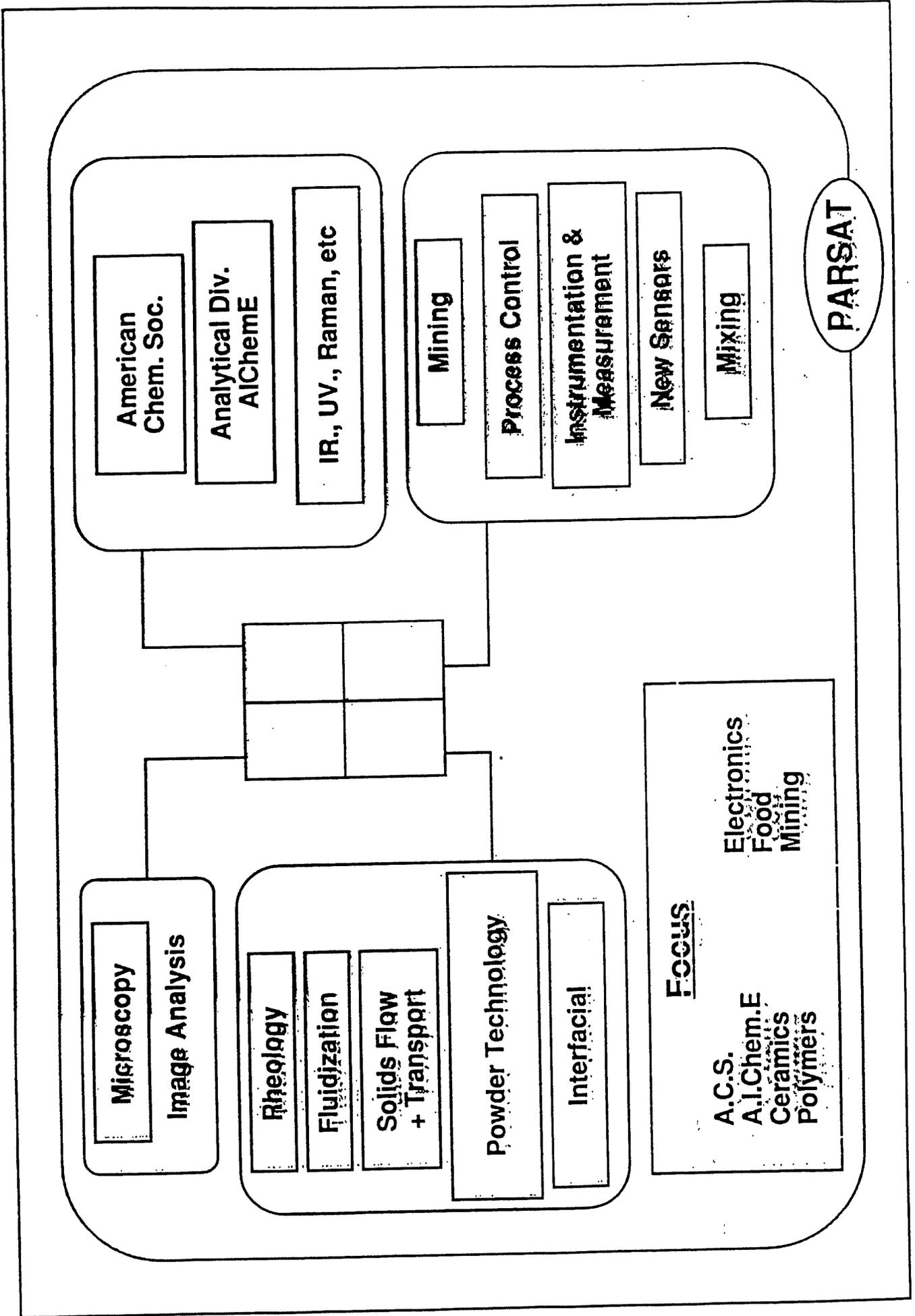
## Bulk Systems

Bulk Density  
Shear Strength  
Tensile Strength  
Flowability  
Caking Resistance  
Attrition Resistance  
Slurry Rheology  
Degree of Dispersion  
Mixedness

## On-Line Systems

Pumped Slurries  
Crystallizers  
Dry Powders  
Granules  
Dilute Pneumatic  
Dense Phase  
Tomography

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LINKS NEEDED OUTSIDE AICHEME

IEEE (Measurement & Instrumentation Soc.)

SME of AIME (Mining)

A.S. Mech. Engg.

A. A. Aerosol Research

Food Processing Inst.

Metal Powders Fed.

A.A. Pharmacy

Parenteral Drug Assoc.

Inst. Powder Metall.

Int. Fine Particle Res. Inst.

I. Chem. E (UK)

Royal Soc. Chem. (Anal. Div.)

Japan Soc. of Powder Tech.

Japan Soc. Mat. Sci.

German Inst. Chem. Engrs.

Group for Adv. Spectroscopic & Physical-Chem. Methods of Analysis (France)

Standards Committees  
ASTM & ISO

PARSAT

# Education

- Physical Characterization as an element in a course on Powder Technology (2-4 hours)
- Physical Characterization as a Subject (20 hours)
- Physical Characterization as a Course offered by AlChemE

PARSAT

# Industrial Needs

- 30 years ago physical characterization was rarely practiced British Pharmacopea, for example, had no requirement for sizing the active ingredient in drugs.
- 20 years ago laboratory instruments became widely available
- 10 years ago industry was applying laboratory data to process control and product improvement.
- Today sees the introduction of on-line control with immediate feedback.

**TODAY'S SLOGAN IS "MAKE IT RIGHT UP FRONT"**

**and on-line control makes this possible**

**PARSAT**

## Summary

- **Education in Powder Technology is essential. This subject is a core subject in many foreign universities but is only just beginning to be accepted in the United States.**
- **Training is required for qualified engineers. Many chemical plants are actually Powder plants and the operating personnel are inadequately trained to operate them.**
- **Societies, such as AlChemE, need to develop Powder Technology course curriculae and organize courses based on these curriculae**
- **Academic bodies, Industrialists and Societies need to be involved.**

PARSAT

# PIONEERING PROCESS APPLICATIONS OF FLUIDIZED BEDS

## **Gas-Solid Fluidized Bed**

Winkler process for coal gasification for production of gas from powdered coal in Germany in 1926.

## **Gas-Liquid-Solid Fluidized Bed (Slurry Bubble Column)**

Bergius-Pier process for direct coal liquefaction for production of motor fuels from lignite in Germany in 1927.

## Gas-Solid Fluidized Beds

### Classical Applications:

- Synthesis reactions — production of phthalic anhydride, maleic anhydride, polyethylene, acrylonitrile, hydrocarbons via Fischer-Tropsch synthesis, etc.
- Cracking of hydrocarbons — FCC, thermal cracking, fluid coking, etc.
- Reduction or oxidation reactions of ores — roasting sulfide ores, reduction of iron ores, etc.
- Carbonization and gasification — coal and coke gasification, and activated carbon production.

## Gas-Solid Fluidized Beds

### State-of-the-Art Applications:

- Material processing – production of silicon, silicon carbide, silicon nitride, tungsten carbide and particles with metallic coatings.
- Clean fossil fuel technology – control of  $\text{NO}_x$ ,  $\text{SO}_2$ ,  $\text{N}_2\text{O}$ , air toxics, liquid & solid wastes and other emissions resulting from coal use; high pressure circulating fluidized bed combustion and fluidized bed incineration of solid wastes.

## **Gas-Liquid-Solid Fluidized Beds**

### **Classical Applications:**

- Physical processing – sand filter cleaning, air flotation, crystallization, etc.
- Chemical and environmental processing – hydrogenation of heptane, Fischer-Tropsch synthesis, flue gas desulfurization, etc.
- Petrochemical processing – hydrotreating and conversion of heavy petroleum and synthetic crude, coal liquefaction, etc.
- Electrochemical processing – fluidized bed electrode.
- Biochemical processing – biological wastewater treatment.

## **Gas-Liquid-Solid Fluidized Beds**

### **State-of-the-Art Applications:**

- Methanol synthesis
- Dimethyl Ether production
- Biological processing to produce antibiotics (e.g., penicillin, patulin, etc.), ethanol, tissue plasminogen activator, enzyme, animal cells, etc.

## **Universities offering courses on Fluidization and/or Fluid-Particle Systems**

- Georgia Inst. of Technology
- Illinois Inst. of Technology
- Worcester Polytech. Institute
- Univ. of Missouri-Columbia
- City University of City College of New York
- Clarkson University
- Cornell University
- University of Akron
- Ohio State University
- University of Pittsburgh
- Texas A&I
- Texas A&M
- West Virginia University
- Others

## **Interaction with PTF**

- Through existing program Area 3b – Fluidization and Fluid-Particle Systems, represented by about 50 program committee members.
- Through existing international working parties on Engineering Foundation Conference on Fluidization (held every three years with 8th conference in 1995) represented by countries including U.S., Japan, P.R. China, Australia, Canada, U.K., France, Germany and Netherlands.

## Examples of Fundamental Areas Requiring Further Research

### Gas-Solid Fluidization

- Elasticity behavior of dense phase particles, or solids stress, in general, in fluidization stability analysis
- Flow behavior in bubble wake and voidage distribution around bubbles in analysis of gas flow division and bubble coalescence & breakup
- Gas kinetics theory approach in dilute and dense phase pneumatic transport simulation
- Mechanism of cluster formation and dynamics of solids flow in core and wall regions and their interaction in fast fluidization
- Characterization of fluidization with fine powders
- Scale-up criteria and fluidization at high temperatures and pressures

## Gas-Liquid-Solid Fluidization

- Theoretical account of flow structure of three-phase fluidization or slurry bubble columns characterized by spiral bubble upflow and vortical liquid-solid downflow motion
- High velocity gas-liquid-solid fluidization
- Numerical study of bubble formation, bubble rising, vortex shedding and macroscopic flow behavior of three-phase fluidization
- Scale-up and three-phase fluidization at high temperatures and pressures

## **PARTICLE TECHNOLOGY FORUM**

### **Solids Transport and Handling Analysis**

Definition: Pneumatic Conveying, Belt Conveyors, Bucket Elevators, Drag Conveyors, Screw Conveyors, Truck, Rail and Barge Transport

**U.S. Competitiveness is affected in as much as these materials affect the entire manufacturing sector of the economy.**

. The availability of energy is compromised if solids are not properly and efficiently transported.

. Mineral usage is a big sector affected by solids transport reliability.

. Dyes and pigments is a large market affected by transport

. Solids transport and handling is involved with an international market where competition is high.

. Active countries in this transport arena are Japan, England, Germany, Denmark, Italy, and Korea.

. Covers wide breadth of technologies from pneumatic conveying to mechanical conveying.

. Dow has located a solid processing center in Germany rather than the U.S.

## **Impact of Solids Transport and Handling on Industry**

. Transport is essential in all processing on large scale (mineral) to small scale (pharmaceuticals)

. Wide variety of industries affected from mineral to food processing

. Merrow... Plants involving solids were found to be operating at an average of 50% of design capacity. Startup times where raw solids entered as feed took 18 months, a considerable delay over the average planned time of 7 months.

. Davies... 60% of Dupont's 3000 products are in powder form and another 20 % depend on particles to impart desired properties.

. Often the transport operation is left to last and given little design consideration.

. Control is essential for these operations but often lacking

. Flow measurements mostly nonexistent.

## **Proposed Interaction with PTF**

- Prepare Sessions
- Establish Standards

- . Design
- . Nomenclature
- . Task Force certain topics i.e. serve as a clearing

house and data bank for information generated by U.S. firms in this area. This information base would eliminate duplication of efforts and presents a saving of money. New areas could be pursued in lieu of the duplication that presently exists. This effort could help to place the U.S. in a more competitive position in the world markets of solids transport and handling area. The PTF would encourage data sharing some of which has been done over 20 years ago.

## Education

- Number of Universities that have courses

  - Research at Universities

  - England, Germany, Japan and Australia

. Tilton... Fluid mechanics education in U.S. chemical engineering departments inadequately prepared graduates to solve or even reorganize, multiphase flow problems. This is unacceptable because these problems sometimes means the difference between success and failure of a commercial process.

. Klimpel... states that universities should work together to develop a meaningful core curriculum in fluid/particle systems for undergraduate engineering students on an interdisciplinary basis.

. It has been stated that about 20 of the Japanese programs in chemical engineering have particle technology as a significant component of their curricula.

. The Education Committee of the AFS has held two week long conferences in January of 1992 and 1993 related to a program of action for introducing course involving fluid/particle and multiphase processing into engineering programs.

## Research Needs

- Reliable Control
- Characterization of Materials for Design
- Scale-up Problems
- Increased Pressure Effects
- Fine Particle Handling, including nano size materials
- Reliable Flow Metering
- Attrition and Erosion Control
- Feeder/Bin Flow Interactions
- Pickup/Saltation Prediction
- Dense Phase Design
- Realistic Modeling and Simulation
- Heat Transfer and Solids Flow
- Diagnostics
- Dense phase analysis and corresponding instrumentation for field usage.
- Particle-particle interactions and electrostatic and drag

- Further development of optical methods for velocity and concentration measurements

- Understanding materials that misbehave for no apparent reason. Small fractions of certain components vital.

SUMMARY OF PRESENTATION  
ON  
PARTICLE MIXING, SEGREGATION, AND CLASSIFICATION  
AT  
THE NSF WORKSHOP ON PARTICLE TECHNOLOGY  
WASHINGTON, D.C.

June 25-26, 1993

## INTRODUCTION

For brevity, particle mixing, segregation, and classification will be termed collectively as particle mixing whenever deemed appropriate. Segregation or classification can be naturally viewed as reversed mixing.

Particle mixing is probably the most widely-employed particulate operation or process. It is involved not only in the chemical, process and allied industries but also in many other industries. In fact, particle mixing is practiced in almost every sector of our society and in our daily life. For example, it is an indispensable operation in building or highway construction, agricultural enterprises, and preparing meals in restaurants and homes.

Particle mixing is unique among the particulate processes. Its uniqueness is attributable to the following.

- a. Particle mixing can be carried out totally independent of other particulate processes. In other words, it can be a stand-alone operation.
- b. Almost all other particulate processes are accompanied by particle mixing, segregation and/or classification. Some examples of such particulate processes are grinding, agglomeration, coating, crystallization, fluidization, heterogeneous reaction involving solid reactants or catalysts, and pneumatic or hydraulic transport.

## EDUCATIONAL NEEDS

Currently, the majority of the educational activities related to particle mixing takes place in continuing education classes at meetings of various technical societies or at trade shows. Apparently, formal course offerings on particle mixing, segregation, and classification are available on few, if any, university campuses. Nevertheless, the indication is that these subjects often occupy a significant portion of courses in pharmaceutical processing, food processing or mineral and material processing.

Chemical and process industries are increasingly involved in particle handling and processing. It is highly desirable, therefore, that the subjects of particle mixing, segregation, and classification be incorporated into appropriate courses in Chemical Engineering, e.g.,

chemical reaction engineering and separation processes.

If sufficient demand exists, an interdisciplinary course or courses on particulate science and technology should be jointly offered by two or more departments or schools. Obviously, a significant fraction of such courses should deal with particle mixing, segregation and classification.

## RESEARCH NEEDS

Much of the research focusing solely on particle mixing is carried out by researchers affiliated with relatively small or medium size companies that fabricate and market particle mixers and blenders. The projects undertaken tend to be "applied" instead of "fundamental." The approaches tend to be "empirical" instead of "theoretical." Moreover, the data and results obtained are seldom published in the open literature.

Numerous facets of particle mixing, both fundamental and practical in importance, remain to be investigated. Yet, such facets of particle mixing are attracting only a very limited number of academic researchers. Some of the problems urgently requiring their attention are listed below.

- A. Particle Systems
  - a. Particles with broad distributions of sizes, densities, and shapes.
  - b. Ultrafine particles necessary for fabricating high-strength ceramics and other advanced materials, e.g., superconductors.
- B. Mixing Methods and Mixers
  - a. Non-conventional methods: The mixing of the particle systems listed in A can be promoted by non-conventional means, some of which include co-dissolution followed by spray drying or crystallization, co-melting followed by rapid solidification and grinding, agglomeration, flocculation, application of electromagnetic forces, and a combination of two or more conventional and/or non-conventional means.
  - b. Batch and semi-batch mixers with non-conventional methods of mixing.
  - c. Continuous flow mixers of various configurations and with different modes of mixing.
- C. Instrumentation and Sensors
  - a. Robust devices for particle characterization: Devices are needed to consistently determine the characteristics of particles based not only on conventional measures but also on non-conventional measures, such as perimeter and surface fractal dimensions, under various environmental conditions.
  - b. Non-intrusive sensors for continuously monitoring compositional changes in mixers.
- D. Particle Mixing in Various Process Equipment

It is obvious that research in this area is essential.
- E. Designs of Mixing and Mixing Systems
  - a. Scale-up of individual mixers: According to an authoritative source, only one

technical paper has been published on the scale-up of a single class of batch mixers. Dimensionless scale-up equations should be established for other classes of mixers.

- b. Process synthesis: Mixing or classification of some particle systems is best accomplished by a group of identical or different mixers or classifiers forming a network. Synthesizing such a network is, more often than not, extremely time-consuming and expensive. It is essential that a highly efficient computer-aided method be developed for process network synthesis.

F. Analysis, Modeling and Theory

In general, particles participating in mixing, segregation, or classification are neither sufficiently microscopic nor sufficiently macroscopic; in other words, they are mesoscopic. The mesoscopic systems can not be readily treated by the concepts and methods of statistical mechanics and molecular dynamics for microscopic systems or by those of classical deterministic physics and continuum mechanics for macroscopic systems. The conventional approaches for analysis and modeling based on the statistics and classical physics yield results which are gross approximations at best. These conventional approaches should be supplemented by the modern approaches appropriate for mesoscopic systems, including those derived from the notions of chaos, fractals, stochastic processes, and percolation.

L. T. Fan  
Department of Chemical Engineering  
105 Durland  
Kansas State University  
Manhattan, KS 66506-5102

August 31, 1993

## POWDER MECHANICS AND SOLIDS FLOW SUB-GROUP

Remarks by Dr. John W. Carson at PTF Workshop  
on June 25, 1993

Almost every industry handles powders/bulk solids, either as in-coming raw materials, intermediates in the production process, or as final product. Examples include: chemicals and chemical processing, foods, detergents, pharmaceuticals, building products, power generation, glass, automotive, agricultural. The total amount of bulk solids handled in the U.S. alone each year is measured in billions of tons.

Powders/bulk solids are stored in containers which go by a variety of names, such as bins, silos, hoppers, and elevators. Processing vessels which are used to purge, dry, heat, cool, or condition materials are also solids handling containers. The capacity of these containers can vary from a few pounds of material such as a press feed hopper used in a pharmaceutical facility, to multi-thousand ton capacity vessels such as train loadout silos at a coal preparation plant. In addition to a wide range of capacities, flow rates vary widely from a few pounds per hour to thousands of tons per hour, and temperatures vary from below-freezing to over 2000°F.

Given the variety of industries involved and the importance of reliable solids flow, it is amazing that this subject is not taught by any college or university in the U.S. as part of a regular course of study. The reasons for this appear to be several:

- This subject falls between several disciplines – primarily chemical, mechanical, and civil engineering.
- It is a difficult subject to teach since extensive practical experience is required to gain an understanding that can be imparted to others.
- There is little or no funding at the university level for research in this field, so it is difficult for faculty to gain the understanding necessary to teach it.

Two notable exceptions to this include Penn State (Particulate Material Center) and The University of Pittsburgh. Also, there are a number of short courses available, including several which have been available for many years through AIChE.

Since this subject is not being taught in college, graduating engineers have no appreciation of the problems which can occur, how to prevent those problems in new facilities, and where to turn when problems develop. As a result, powder/bulk solid handling has become a neglected area in the design of new plants and processes, and the same mistakes are repeated over and over. This in turn causes slow plant start-ups (see Merrow/Rand study), inefficient production, poor quality control, and safety hazards such as dust emissions and silo collapse. Clearly this affects U.S. competitiveness.

Since few plant engineers have the necessary technical background and experience to know what to do to avoid solids flow problems (or how to solve such problems when they develop), they often turn to equipment vendors, A/E firms, and consultants. Unfortunately few of the individuals in these firms have very extensive training in this field either, so what they recommend is often wrong or, at best, inefficient.

There are a number of U.S. laboratories which specialize in the measurement of solids flow properties. Independent labs consist of Jenike & Johanson, Inc., H. Colijn & Associates, J. R. Johanson, Inc. and BBC&M. Some of the largest U.S. industrial companies have set up their

own in-house solids flow laboratories. Among them are Procter & Gamble, DuPont, Dow Chemical, Union Carbide, and Rhone Poulenc.

Key research needs in this field consist of the following:

1. Better constitutive laws. The state of a bulk solid throughout a container is described in terms of its stress field. The solid's instantaneous response is described in terms of a velocity field over the region where it is flowing. The link that ties the stress field to the velocity field is called the constitutive relation.

The first successful attempt to describe bulk solids flow in a hopper was proposed over 30 years ago by Jenike, who was primarily interested in describing mass flow behavior. Assuming a steady-state condition, he imposed a flow rule on the stress state which allowed uncoupling the stress field from the velocity field. While this approach works well for mass flow, it cannot be used for funnel flow because the boundary between flowing and stagnant material is not fixed. In addition there is an elastic response within the stagnant material and a changing velocity field within the flowing material. Therefore a constitutive relation that maps strains and strain rates onto the stress state is required. Attempts have been made to develop such a relationship, but much more needs to be done.

2. 3-D computer programs. Once more accurate constitutive relations have been developed, numerical methods can be used to analyze complex stress and velocity fields within containers. Whether finite element, finite difference, or some other numerical technique is used depends in part on the form of the resulting equations. While the finite element technique appears to have significant appeal, it cannot adequately model stress and velocity discontinuities such as those which occur at characteristics. For this reason, perhaps a finite difference technique would be more appropriate since this is well-suited to solving hyperbolic type, partial differential equations.

Another approach involves the modeling of the bulk material by discrete particles. This has the added benefit of capturing segregation, non-isotropic behavior, and other unusual conditions. With computer speeds doubling about every 18 months, this method certainly bears consideration.

No matter what method is used, it is important that the resulting programs be able to handle bins/silos of arbitrary geometry with either single or multiple outlets. Static, transient, and steady-state behavior should be included, as well as single-phase (solids only) and multi-phase (solids/gas or solids/liquids) behavior.

3. Bin loads. Of the three major aspects of silo design (bulk material, geometric, and structural), the bin loads aspect of structural design is the least understood. Unfortunately, if the structural design is not done properly, the integrity of the silo may be compromised. Silo collapse is far too common, yet agreement amongst designers on procedures for determining silo loads has not been forthcoming. This is very apparent when one considers existing codes of practice. There is little detailed guidance concerning the various loading conditions – some static, some dynamic – which can co-exist.

In conclusion, what is needed is a recognition by government, industry, and academia of the importance of powder mechanics and solids flow to U.S. industry. Such recognition must be tangible, particularly in the form of financial support of research, as well as industry/academic collaboration on problems of common interest.

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**DISPERSIONS AND INTERFACIAL PHENOMENA**

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AICHe - PTF WORKSHOP  
Washington, D.C

Brij M. Moudgil  
Mineral Resources Research Center  
Department of Materials Science & Engineering  
University of Florida  
Gainesville, FL 32611

June 25-26, 1993

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## TERMINOLOGY

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**AGGLOMERATION:** The process of producing agglomerates. Often involves binder to improve cohesion or redispersion in a liquid in subsequent processing.

**AGGREGATES:** Strongly bonded clumps.

**COAGULATION:** Any sort of agglomeration of particles in a liquid. Specifically refers to strong, primary well coagulation as opposed to weak, secondary well flocculation.

**FLOCCULATION:** The process of particles sticking together into rather weakly bonded and open structures (high void fraction) known as flocs.

**DISPERSION:** Suspension of powders in liquids.

- |                                   |  |
|-----------------------------------|--|
| - Ceramic Slurries                | - Electronic Insulators                            |
| - Magnetic Media for coatings     | - High Quality Paper                               |
| - Drilling Muds                   | - Silver Dispersions for Electronic Circuit Boards |
| - Textile Fibers                  |  |
| - Cosmetics, Health Care Products |  |

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## DISPERSION MECHANISMS

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Electrostatic Stabilization - For liquids with high dielectric permittivity and low ionic strength, ex. silicates, polyphosphates.

For organic liquids - quarternary amines

Monolayer coverage required.

Steric Stabilization - Dispersants with a higher HLB values for aqueous dispersions, and a low HLB for dispersions in nonpolar liquids.

Adsorption of surfactants or polymers required to obtain a stable dispersion.

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## THREE STAGES OF DISPERSION PROCESS

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I. Wetting the surface and displacing air. Occluded air displaced by liquid. No agitation needed if:

- (i)  $\rho_{\text{powder}} > \rho_{\text{liquid}}$
- (ii) liquid wets the powder, and
- (iii) clump not strongly agglomerated

Otherwise, agitation needed to draw the powder into bulk of liquid, keep it there, and break the agglomerates

II. Deagglomeration of Clumps

- Wetting does not ensure good dispersion
- Milling required to break solid-bridge bonds
- Surfactants sometimes used as grinding aids

III. Maintaining Particle Separation

Stability of dispersion:

- May require moderate shear
- Sedimentation prevented by weakly flocculating the entire dispersion

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## **IMPORTANCE TO US COMPETITIVENESS**

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Improved and cost effective product performance  
critical to US competitiveness in global markets.

Understanding particle-particle interactions to  
develop adequate process control necessary to meet  
the above objective.

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## LINKAGE TO INDUSTRY AND PROFESSIONAL SOCIETIES

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- \* Dispersion and Interfacial Phenomena of major significance in Chemical, Mineral, Ceramic, Pharmaceutical, Environmental Restoration, and Health Care industries.
  
- \* Besides AIChE other societies addressing dispersion, flocculation and other interfacial phenomena topics include:
  - Society for Mining, Metallurgy, and Exploration Inc. (SME)
  - American Ceramic Society
  - American Chemical Society
  - American Filtration Society
  - American Fine Particle Society
  - Institution of Mining and Metallurgy
  - Australasian Institute of Mining and Metallurgy
  - European Federation of Chemical Engineering
  - Japan Society of Powder Technology

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## CURRENT STATE OF STUDENT EDUCATION

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- \* Fragmented at best
- \* Very few courses on Particulate Technology
- \* Students take only a few courses related to Interfacial Phenomena
- \* American Filtration Society preparing an outline of five courses for a minor in solid-fluid interactions/separations

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## INTERACTION WITH PTF

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- \* Interfacial Phenomena a core discipline in PTF
- \* Technical information exchange at meetings/workshops sponsored by PTF
- \* Assist PTF in developing and prioritizing education thrusts and emerging research topics

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## RESEARCH NEEDS

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- \* Correlation between polymer conformation and particle-particle interactions
  - Models with predictive capabilities
- \* In-situ characterization of dispersions/flocculation suspensions
  - Sensors
  - Instrumentation
- \* Influence of radioactive exposure and biological molecules/species on particle-particle interactions
  - Environmental restoration applications
- \* Decomposition/Recycle characteristics of dispersants, flocculants
- \* Scale-up and process control

## Suspension and Slurry Rheology Subsection Report for the NSF-PTF Workshop

Gerald G. Fuller  
Chemical Engineering  
Stanford University  
Stanford, CA 94305-5025

Rheology is defined as the science of deformation and orientation processes of materials subject to flow. In this respect, rheology is an interdisciplinary subject, requiring a synthesis of knowledge from fluid mechanics and materials science. The transport of rheologically complex suspensions, slurries and dispersions is commonly encountered in industrial processes. It impacts the design and operation of processes for long standing products such as cements and food doughs, as well as newer technologies such as those leading to the creation of advanced composite and ceramic materials.

An extensive list of US industries can be generated whose business involve flow processes of complex particulate liquids. Such an itemization would include (1) the chemical industry: catalysis particles, ceramics, and polymer dispersions, (2) pharmaceutical industry: particulate medications, cell/plasma separators, (3) oil/energy industry: slurry (coal) transport, catalysis particles, (4) paper industry: coating flows of suspensions, (5) aerospace industry: composites, solid propellants, (6) electronics industry: particulate magnetic media, ink-jet printing, polymer-dispersed liquid crystal displays, (7) automotive industry: composites, ceramics, and electro-rheological fluids, (8) food industry: slurry and dough transport, and (9) personal products industry: creams, soaps and pastes.

In each of these industries the importance of suspension rheology may not be immediately obvious to the end user since the suspension or dispersed state only exists during intermediate processing steps. Nonetheless, the rheological behavior during that step can be critical to the final performance and appearance of the product. Examples can be drawn to illustrate this situation from products derived from polymer particle dispersions. These would include (1) reinforcers for carpet backs where styrene-butadiene-copolymers dispersions are used, (2) safety gloves made from butadiene-acrylonitrile-copolymer dispersions, (3) water and oxygen barriers in packaging materials made from thin polymer dispersion coatings and (4) paper coatings for high quality printing. These examples all have in common an original state consisting of highly concentrated dispersions of polymer particles. Rheology is important during polymerization (stirring, heat transfer), transportation through pipes and orifices, and during the final processing step (often a coating flow). The rheology of the dispersion normally has to be appropriately matched to achieve desirable properties, such as surface quality.

In recognition of the importance of particulate fluid rheology, many scientific and professional societies promote meetings and symposia where results representing the state of the art can be communicated. Nationally, the primary organization promoting this activity is the Society of Rheology, but regular sessions and symposia are also supported by the A.I.Ch.E through its Fluid Mechanics and Material Science Divisions. In addition, the ACS Colloids Division frequently will sponsor sessions during its spring meeting. Participation by industrial researchers at these meetings is encouraged and the organizers are normally strive to strike a balance between academic and industrial laboratory participants. Industry also supports funding of research either through direct collaboration with principal investigators, or through industrial consortia. the International Fine Particle Research Institute is a fine example of the latter funding vehicle, and that organization has funded research in rheology since its inception.

The international community of researchers in this area is well developed. Each national society of rheology strongly supports the dissemination of research on particulate fluid rheology at

their annual meetings, and once every four years the International Congress on Rheology meets and this topic is a principal component of the meeting. The research activities in the US, Europe and Japan are equally balanced, with no geographical region having dominance in this field.

Education of undergraduate and graduate students in the field of rheology, and in the area of particulate fluid rheology in particular, widely varies between institutions and normally depends on the presence of active researchers in this area. At the undergraduate level, students receive instruction in fluid mechanics (chemical and mechanical engineers normally receive greater training than other disciplines), but this rarely includes non-Newtonian materials. Particulate fluid mechanics at this level would normally only consider single sphere problems. At the graduate level, courses on rheology can often be found, but they would not normally specifically address particulate fluids. Rather, continuum rheological constitutive equations are usually be discussed. Lectures relating the microstructure of complex fluids to their rheology almost exclusively deal with polymeric materials, since those theories and models are more extensively developed. Opportunities do exist, however, for current theories on nonequilibrium dispersion and suspension microstructure to be presented at the senior undergraduate and graduate level, and attention should be given to the development of course materials.

Research on particulate fluid rheology and the subsequent fundamental knowledge it provides can be of critical importance to the development of new technologies and the optimization of current manufacturing processes. Three principal, overall objectives can be defined: (1) the development of accurate rheological constitutive equations for use in the modeling and simulation of non-Newtonian flow processes for these materials, (2) the development of rheological protocols for the proper characterization of complex particulate fluid materials, and (3) the development of on-line and in-line measurement probes of structure and kinematics to monitor and control processes.

To accomplish these ultimate objectives, the following lines of research should be targeted:

- Simulation of suspension dynamics and structure: Recent progress in simulating the flow behavior of suspended spheres at high volume fraction has provided important insight into the mechanisms associated with a variety of anomalous rheological phenomena, such as shear thickening. These results can be used to suggest which physical mechanisms should be included and whether simplifying assumptions can be used for analytical constitutive models.
- Statistical mechanical based constitutive equations: Analytical rheological constitutive models that must be developed for use in non-Newtonian flow simulations must recognize the specific microstructures of particular suspension systems. Such models are necessarily developed within the context of statistical mechanics.
- Continuum rheological models: Numerical modeling of non-Newtonian fluid mechanics requires the input of rheological models that need the input of continuum, macroscopic variables. In order to generate models that depend on specific microstructures, this must be accomplished in concert with the results of simulations and statistical mechanical theories.
- Structural measurements: The development of constitutive models that are sensitive to the specific structure of suspensions requires the availability of *in situ* microstructural measurements made under a variety of steady and transient flow conditions. Techniques such as small angle light scattering, NMR tomography, small angle neutron scattering should be applied along with mechanical rheology measurements to establish structure-property relationships.
- Kinematic measurements: Since constitutive equations establish the relation between the stress tensor (or structure) and the kinematics of the flow, research should be supported to develop methods such as NMR tomography and diffusing wave dynamic light scattering that can obtain this information.

**NO INFORMATION PROVIDED**

**PARTICLE TECHNOLOGY FORUM**

**Workshop Sponsored by NSF June 25-26, 1993**

**Pharmacy Subgroup**

**Summary of the Area of Activity**

**David J. W. Grant**

**Department of Pharmaceutics  
College of Pharmacy  
University of Minnesota  
Health Sciences Unit F  
308 Harvard Street S.E.  
Minneapolis, MN 55455-0353**

## 1. Introduction

Pharmacy is a health science that embraces the fields of medicinal chemistry, pharmacology, pharmaceuticals and pharmacy practice. These fields of activity are carried out both by the pharmaceutical industry and by colleges of pharmacy. The pharmaceutical industry develops, manufactures and markets therapeutic chemical entities (drugs) and the ultimate dosage forms (pharmaceuticals). Colleges of pharmacy are responsible for educating pharmacists, both as pharmaceutical scientists for the pharmaceutical industry, and as health care professionals who are responsible for providing pharmaceutical care to patients in hospitals and in community pharmacies. Colleges of pharmacy award the bachelor's degree, which is analogous to the bachelor of science, medicine or dentistry but is likely to be discontinued before the year 2000, and the degree of doctor of pharmacy, which is a professional degree not involving graduate studies, that is analogous to the doctor of medicine or dentistry. In addition to these undergraduate or professional degrees, colleges of pharmacy may provide graduate programs in each of the various specific fields of pharmacy leading to M.S. and Ph.D. degrees in that field. These graduate degrees are analogous to graduate degrees in other scientific fields and their major function is to educate pharmaceutical scientists for the pharmaceutical industry. The Ph.D. degree from a graduate department in a college of pharmacy has a high academic standing culminating in a scholarly, publishable thesis.

## 2. The Field of Pharmaceutics

In pharmacy, pharmaceutics is the field of study with which particle technology is most closely associated. Pharmaceutics involves (a) the design, development, formulation and evaluation of delivery systems, i.e. dosage forms, for drugs, the biological area of which is termed biopharmaceutics, (b) the study of the physical and chemical properties and stability of drugs and dosage forms, which is termed physical pharmacy, (c) the knowledge base for the manufacture and evaluation of dosage forms, which is termed pharmaceutical technology or industrial pharmacy, and (d) the rates and amounts of absorption, metabolism and excretion of drugs in the body, which is termed pharmacokinetics.

## 3. Importance of Particle Technology in Dosage Forms

Dosage forms consist of one or more biologically active chemical entities, i.e. drug(s), and one or more biologically inactive substances, termed excipients. The function of the excipient is to confer desirable physical or chemical properties on the drug or dosage form, such as dilution, dispersion, stabilization, binding, aggregation, agglomeration, or lubrication. All dosage forms contain components, the drugs and excipients, that at some stage are in a particulate form. Consequently, particle technology is the core knowledge base critical to pharmaceutics, to pharmaceutical dosage forms and to the pharmaceutical industry, for example, in drug processing and in dosage form design, manufacture, performance and clinical efficacy. For example, after administration of a tablet to a patient, the rate and extent of absorption of the drug in the gastro-intestinal tract usually depends on the rate of dissolution of the drug, which in turn depends on the rate and extent of disintegration of the tablet after swallowing and wetting, the accessible surface area of the drug particles and the particle shape and size distribution in the tablet.

The advent of new and improved drug delivery systems, some involving biotechnology, peptides and proteins, establishes an even greater need to control particle properties at the molecular, particulate and bulk levels, including phase analysis, crystallinity, crystal defects and crystal habit, i.e. shape. Particle technology is critical to most pharmaceutical patents, innovations and submissions to regulatory agencies, such as the Food and Drug Administration (FDA), for product approval.

Most pharmaceuticals contain dispersed particles, e.g. tablets, capsules, emulsions, suspensions, ointments, creams, aerosols, nebulizers, and nasal, bronchial, pulmonary and transdermal delivery systems. Although a few pharmaceutical products are homogeneous systems, e.g. injectible solutions, these must be free of particles, requiring sensitive methods for particle detection and characterization, again involving particulate technology.

In view of the foregoing discussion, it can be readily seen that the processing, design, development, function, manufacture, performance and evaluation of dosage forms depends on all the various divisions or subgroups of particle technology, namely:

- Particle Formation in Gases
- Crystallization & Precipitation
- Size Enlargement & Agglomeration
- Comminution & Attrition
- Tribology, Friction, & Interparticle Forces
- Particle Characterization
- Fluidization & Multiphase Flow
- Solids Transport & Handling
- Particle Mixing, Segregation & Classification
- Powder Mechanics & Solids Flow
- Dispersions & Interfacial Phenomena
- Suspension & Slurry Rheology

To this list, may be added deposition, tableting, granulation, erosion, drying, sintering, and simulation of particle processes.

#### 4. Linkages Between Pharmaceutical Particulate Technology and Other Global and Domestic Societies

The primary domestic professional society for pharmaceutical scientists is the American Association of Pharmaceutical Scientists (AAPS) which has over 5,000 members, including many international members, and comprises eight sections, including three that are relevant to particle technologists, namely Pharmaceutical Technology, Pharmaceutics and Drug Delivery, and Analysis and Pharmaceutical Quality. AAPS has high international standing. Each of the major industrialized countries has its own domestic society for pharmaceutical scientists in which particulate technology features strongly. Many pharmaceutical scientists are also members of major scientific societies, such as AIChE, and/or ACS, which may be related to their primary knowledge base, and/or major professional societies, such as the American Pharmaceutical Association (APhA) and the Fédération Internationale Pharmaceutique (FIP).

The importance of particle technology in the safety and efficacy of pharmaceuticals has long been recognized by the FDA, mentioned above, which is responsible for the legal approval of drugs, excipients and pharmaceutical products, and by the United States Pharmacopoeial Commission (USP Commission), which publishes the United States Pharmacopeia/National Formulary (USP/NF). The USP/NF provides guidelines for the quality and testing of drugs, excipients and pharmaceutical products. In 1991 the USP Commission appointed an Advisory Panel on Physical Test Methods. Most of these methods are applicable to powders and involve various applications of particulate technology.

5. Particle Technology and the Pharmaceutical Industry

Particle technology tends to be involved in different disciplines, areas and directorates within pharmaceutical companies, for example, preformulation in the research directorate, particle characteristics in the formulation area, and bulk properties of powders in the manufacturing area. As a result, particle technology is often poorly coordinated within pharmaceutical companies.

Fortunately, some of the larger companies are now developing coordinated approaches by establishing a specialist group of expertise to coordinate experience, to provide a knowledge data-base and to offer advice. Many companies have established, or are establishing, interactions and collaborative relationships with universities and research institutes to help solve problems creatively. These collaborative efforts provide these institutions with valuable opportunities for research funding, student education, and student employment.

On a small scale, pharmacists in hospitals and, to a lesser extent, in community pharmacies are sometimes required to prepare pharmaceutical products for which some knowledge of particle technology is required. This procedure is termed "extemporaneous compounding."

6. Influence of Pharmaceutical Technology on the Competitiveness of the U.S. Pharmaceutical Industry

The competitiveness of the U.S. pharmaceutical industry depends enormously on particle technology. If there is a poor understanding of the behavior of materials and particles, product performance may not be optimized and industrial competitiveness will be compromised. The pharmaceutical industry requires greater predictive capability which particle technology can provide, thereby leading to the optimization of products and to improved competitiveness.

The major pharmaceutical companies are based in industrialized countries such as the USA, Japan, Germany, UK, Switzerland, France, Italy and Sweden. However, the multinational nature of many of these companies greatly facilitates the transfer of technology to and from the USA, thereby leveling some of the competitive international pressures.

7. Current State of Education of Students in Pharmaceutical Particulate Technology in the USA

Undergraduate pharmacy courses in pharmaceutical particulate technology during the last two decades have suffered serious erosion, almost to the point of extinction in some colleges, in favor of professional courses in pharmacy practice, that is clinical, hospital and community pharmacy. However, to maintain high professional standards, undergraduates in pharmacy programs need practical experience in handling particulate systems, for example, particle sizing, powder flow, capsule filling and tableting.

Graduate courses in pharmaceutical particulate technology are limited in many graduate programs in pharmaceuticals, but should certainly include theoretical and practical instruction on dispersed and particulate systems. However, newer courses in dosage form design and drug delivery, for example, of peptides, proteins and other biological materials, are encouraging the introduction of particulate technology and materials science into graduate programs.

8. Key Research Needs in Pharmaceutical Particulate Technology

The fundamental materials science of the organic solid state is an emerging area that needs further development in view of the great variety of molecular structures of drugs and excipients. Links are emerging and need to be clearly established between these molecular structures, the corresponding intermolecular interactions and crystal structures, and the physical properties and behavior of drugs and excipients at the crystal or particulate level and at the bulk powder level. Examples of such properties include thermodynamic properties, solubility and specific surface area, (and hence dissolution rate), elastic modulus, yield strength, hardness, plasticity (and hence compactibility and tableting performance), surface properties, rigidity, surface free energy, drug-polymer interactions (and hence the preparation and properties of granules and new drug delivery systems). The emerging areas of crystal engineering, crystal defects and crystal solvation need further development among drugs and excipients while the crystallization of biological materials, proteins and peptides needs to be better understood. Since many drugs are chiral, the solid-state chemistry of the enantiomers and racemates, especially in particulate systems, needs further investigation. The varied knowledge outlined above should facilitate means of predicting and designing optimal particulate properties and of avoiding interbatch differences for the preparation and processing of particulate materials in the design and manufacture of pharmaceutical products.

Short-term research for solving everyday practical problems is often pragmatic, semi-quantitative and semi-empirical, but is nevertheless still needed and cannot be ignored. Examples are: conveying and fluidizing a problematic powder; improving the tableting performance of a problematic crystalline drug. However, in the long run, the elements of empiricism need to be replaced by fundamental materials science and particulate technology to enable the design, performance and manufacture of pharmaceuticals to be optimized.

9. Possible Interactions With, and Contributions From, the Pharmacy Subgroup Within the Particle Technology Forum

Short courses, workshops and seminars highlighting some specific areas of current and future interest to pharmaceutical particulate technology could involve virtually all subgroups of the forum. Examples could include: particle sizing problems and constraints; specific surface area measurements; powder flow; powder compaction (tableting); particle adhesion and cohesion; crystallization of pharmaceuticals; the challenges of high purity and high yield; production of ultrafine particles for inhalation (aerosol drug delivery systems); production of particles or powders with specific features.

To bring together pharmaceutical and other particle technologists and scientists and to link pharmaceutical research more closely with other particle and chemical engineering areas, interdisciplinary or bridging meetings, seminars or workshops could be introduced. These activities could include plenary lectures focusing on specific areas, and contributed podium or poster sessions to provide forums for exchange of ideas and views.

## 1st INTERNATIONAL PARTICLE TECHNOLOGY FORUM

Wednesday, August 17  
8:00-9:00 AM  
Colorado Ballroom E

**Plenary Lecture on Particle Technology and the Environment: On The Purification of Gas, Water, & Soil and the Recovery of Waste Materials**

Prof. K. Leschonski  
Technische Universität Clausthal  
Institute for Particle Technology and  
Environmental Technology  
Leibnizstrasse 19  
38678 Clausthal-Zellerfeld GERMANY

[55] Wednesday, August 17  
9:00-12:30 AM  
Colorado Ballroom H

**Particle Characterization I**

Sponsored by the Particle Technology Forum

R. Davies, *Chair*  
E.I. duPont de Nemours & Company, Inc.  
Center for Particle Science & Technology  
Experimental Station, E304A224  
Wilmington, DE 19880

B. Scarlett, *Co-Chair*  
Delft Univ. of Technology  
Dept. of Chemical Engineering  
2600 GA Delft, THE NETHERLANDS

Opening Remarks: R. Davies

Invited Paper: Thirty Years in Particle Size Analysis  
• 9:05 AM • Paper No. 55a • T. Allen, DuPont  
Company, Wilmington, DE

Development of Simultaneous Measurement  
Method of the Particle Concentration and Size  
Distribution Using Anisokinetic Sampling •  
9:35 AM • Paper No. 55b • H. Tsuji; H. Makino,  
M. Kimoto, H. Yoshida, K. Inoya, Yokosuka  
Research Laboratory, 2-6-1 Nagasaka, Yokosuka-shi,  
Kanagawaken 240-01, JAPAN

Validation of Particle Concentration Distribution  
Within a Hydrocyclone By Using Tomographic  
Imaging • 9:50 AM • Paper No. 55c • T. Dyakowski;  
R.A. Williams, M.S. Beck, UMIST, Manchester, UK

In Situ Measurement of Particle Size Distributions  
in Concentrated Suspensions • 10:05 AM • Paper  
No. 55d • U. Kräuter; U. Riebel, Universität  
Karlsruhe, D-76128 Karlsruhe, GERMANY

Accurate Droplet Size Distribution Measurement in  
non-Diluted Emulsions using Acoustic Spectroscopy  
• 10:20 AM • Paper No. 55e • F. Alba; C.L. Dobbs  
(Alcoa), R.G. Sparks (Alcoa), Felix Alba Consultants,  
Inc., Murray, UT

Break—10:35 AM

Mobil High Volume Dust Sampler for Fluid  
Catalytic Converters • 10:50 AM • Paper No. 55f •  
A. Avidan; G.K. Chitnis, S.J. McGovern, M. Edwards,  
Mobil R&D Corporation, Paulsboro, NJ

The API Aerosizer: Time-of-Flight Aerosol Beam  
Spectrometry • 11:05 AM • Paper No. 55g •  
B. Dahneke, Amherst Process Instruments, Inc.,  
Hadley, MA

Determination of the Local-Particle-Concentration  
Frequency Distributions of Dispersed Phases in  
Flows Using Pulse Holography • 11:20 AM • Paper

No. 55h • H. Umhauer; P. Neumann, Institut für  
Mechanische Verfahrenstechnik und Mechanik,  
D-76128 Karlsruhe, Box 6980, GERMANY

Measurement of Instantaneous Particle Density by  
Laser Phase Doppler Analyzer • 11:35 AM • Paper  
No. 55i • S.L. Soo; R.E. Van de Wall, University of  
Illinois at Urbana-Champaign, Urbana, IL

Morphology of Cumminuted particles and the  
Measurement of Size Distribution • 11:50 AM •  
Paper No. 55j • C.L. Schneider; R.P. King, The  
University of Utah, Salt Lake City, UT

Interim Remarks—12:05 AM

[56] Wednesday, August 17  
1:30-4:35 PM  
Colorado Ballroom H

**Particle Characterization II**

Sponsored by the Particle Technology Forum

H. Umhauer, *Chair*  
Institut für Mechanische Verfahrenstechnik  
und Mechanik  
Universität Karlsruhe (TH)  
D-76128 Karlsruhe, Box 6980 GERMANY

S.L. Soo, *Co-Chair*  
University of Illinois at Urbana-Champaign  
Department of Mechanical and Ind. Engineering  
1206 West Green Street  
Urbana, IL 61801 USA

Invited Paper: On-Line Particle Size Measurement  
• 1:30 PM • Paper No. 56a • B. Scarlett, Delft  
University of Technology, 2600 GA Delft, THE  
NETHERLANDS

On-Line Particle Characterization by Image Analysis  
Techniques: Multi-Phase Particle Identification and  
Recognition • 2:00 PM • Paper No. 56b • G. Bonifazi;  
P. Massacci, Università Degli Studi di Roma—La  
Sapienza, Via Eudossiana, Rome 18 00184, ITALY

On the Use of Azimuthal Spatial Frequencies in  
Diffraction Patterns for Particle Shape characterization  
• 2:15 PM • Paper No. 56c • C.M.G. Heffels;  
D. Heitzmann, B. Scarlett, TU Delft, 2628 CA Delft,  
THE NETHERLANDS

Using Light Scattering Technique for Kinetic  
Studying of Fine Particle Aggregation • 2:30 PM •  
Paper No. 56d • Y. Ni; S. Lu, University of Science  
and Technology, Beijing, CHINA

Characterization of Aggregate Size Using Static  
and Dynamic Light Scattering • 2:45 PM • Paper  
No. 56e • R. Amal; A. Mardirossian, University of  
New South Wales, Kensington, NSW 2033, AUSTRALIA

Break—3:00 PM

Particle Shape Grouping and Characterization by  
the Coordinate Detection Function with Fourier  
Analysis • 3:15 PM • Paper No. 56f • T. Shibata;  
T. Tsuji, O. Uemaki, K. Yamaguchi, Hokkaido  
University, Sapporo 060, JAPAN

Word By Word Processing for Particle Image  
Analysis • 3:30 PM • Paper No. 56g • X. Ma,  
Institute of Chemical Metallurgy, Beijing, 100080,  
CHINA

Particle Characterization by Means of the Projected  
Area • 3:45 PM • Paper No. 56h • A. Gutsch;  
H. Umhauer, F. Löffler, Institut für Mechanische  
Verfahrenstechnik und Mechanik, D-76128 Karlsruhe,  
Box 6980, GERMANY

Summary

SUMMARY PAPER: Particle Characterization •  
4:00 PM • Paper No. 56i • Dr. Reg Davies,  
E.I. duPont de Nemours & Company, Inc.,  
Wilmington, DE

Discussion & Concluding Remarks—4:30 PM

[57] Wednesday, August 17  
9:00-12:30 AM  
Colorado Ballroom G

**Agglomeration & Size Enlargement I**

Sponsored by the Particle Technology Forum

B.J. Ennis, *Chair*  
DuPont Company  
Agricultural Products & Center for  
Particle Science & Technology  
Experimental Station, E402/25508  
Wilmington, DE 19880-0402 USA

W. Pietsch, *Co-Chair*  
Kopperrn Equipment, Inc.  
3055 Grant St.  
One Oxford Centre, Suite #4260  
Pittsburgh, PA 15219

Opening Remarks: B.J. Ennis

Invited Paper: Advances in the Modeling and  
Simulation of Granulation Circuits • 9:05 AM •  
Paper No. 57a • K. Sastry, University of CA,  
Berkeley, Berkeley, CA 94720, USA

Physically Based Dynamic Models for Simulation  
and Control of Granulation Circuits • 9:35 AM •  
Paper No. 57b • J.D. Litster; F.Y. Wang,  
I.T. Cameron, J. Zhang, University of Queensland,  
QLD 4072, AUSTRALIA

Numerical Simulation of Combined Fracture and  
Coalescence • 9:50 AM • Paper No. 57c •  
J.W. Gentry; S.-H. Cheng, J.C. Lin, R.V. Calabrese,  
M.B. Ranade, University of Maryland, College Park, MD

On Modelling and Significance of the Crusher  
Performance on the Stability of a Granulation  
Circuit • 10:05 AM • Paper No. 57d • A. Adelayo;  
B.J. Ennis, DuPont Company, Wilmington, DE

Modeling of Continuous Granulation in a Fluidized  
Bed • 10:20 AM • Paper No. 57e • T. Koch,  
K. Sommer; Tech. Universität München, Freising-  
Weihenstephan, GERMANY

Break—10:35 AM

Optimization of Feed Size Distribution in Fluidized  
Bed Granulation • 10:50 AM • Paper No. 57f •  
B. Waldie, Heriot-Watt University, Riccarton,  
Edinburgh EH14 4AS, UK

Effect of Solvent Surface Tension, Contact Angle,  
pH, and Surface Chemistry on the Strength of Fine  
Powder Agglomerates • 11:05 AM • Paper No. 57g  
• A. Maskara; D.M. Smith, The University of New  
Mexico, Albuquerque, NM

Influence of Traces of n-Octanoic Adipic Acid  
Crystals on Hiestand's Indices of Tableting  
Performance of the Crystals • 11:20 AM • Paper  
No. 57h • D. Grant; and D. Law, University of MN,  
Minneapolis, MN

A Compaction Study of Alumina Powders •  
11:35 AM • Paper No. 57i • B.J. Briscoe; N. Ozkan,  
I. Aydin, Imperial College of Science, Technology &  
Medicine, Kensington, London SW7 2BY, U.K.

The Packing of Alumina Powders • Paper No. 57j •  
A.B. Yu; J.S. Hall, R.P. Zou, R.M. Anthony,  
The University of New South Wales, Kensington,  
NSW 2033, AUSTRALIA

Interim Remarks—12:05 AM

[58]

Wednesday, August 17  
1:30-4:35 PM  
Colorado Ballroom G

## Agglomeration & Size Enlargement II

Sponsored by the Particle Technology Forum

G. Tardos, *Chair*  
City College of CUNY  
5540th St. & Convent Av.  
New York, NY 10031 USA

J. Litster, *Co-Chair*  
University of Queensland  
Department of Chemical Engineering  
QLD 4072 AUSTRALIA

### Opening Remarks

**Invited Paper: Particle Agglomeration in High Speed Mixers** • 1:30 PM • *Paper No. 58a* • H.G. Kristensen, Danmarks Farmaceutiske Højskole, København Ø, DENMARK

**Agglomerate Coalescence** • 2:00 PM • *Paper No. 58b* • M.J. Adams\*, Unilever Research (Port Sunlight Laboratory), Bebington, Wirral, UK, G. Lian, C. Thornton, Aston University, U.K.

**Monitoring Granulation Processes Using Mixer Torque Rheometry** • 2:15 PM • *Paper No. 58c* • P. York\*, R.C. Rowe, University of Bradford, West Yorkshire, UK

**An Investigation of the Kinetics of Granulation Using a High Shear Mixer** • 2:30 PM • *Paper No. 58d* • P. Knight\*, Unilever Research, Bebington, Wirral UK

**Hierarchical Ordering of Particle Mixtures by Solid-Solid Micro-encapsulation** • 2:45 PM • *Paper No. 58e* • P.R. Mort\*, R.E. Riman, Procter & Gamble Company, Cincinnati, OH

Break—3:00 PM

**Granulation of Hygroscopic Biomaterials (Enzyme Powders)** • 3:15 PM • *Paper No. 58f* • H.O. Kono, West Virginia University, Morgantown, WV 26506, USA

**Invited Paper: Parameters To Be Considered During the Selection, Design, and Operation of Agglomeration Systems** • 3:30 PM • *Paper No. 58g* • W. Pietsch\*, Kopperrn Equipment, Inc., Pittsburgh, PA

### Summary:

**SUMMARY PAPER: Agglomeration & Size Enlargement** • 4:00 PM • *Paper No. 58h* • Dr. B.J. Ennis, E.I. duPont de Nemours & Company, Inc., Wilmington, DE

Discussion & Concluding Remarks—4:30 PM

[59]

Wednesday, August 17  
9:00-12:30 AM  
Colorado Ballroom J

## Crystallization & Precipitation I

Sponsored by the Particle Technology Forum

A. Myerson, *Chair*  
Polytechnic University  
School of Chemical & Materials Science  
Six MetroTech Center  
Brooklyn, NY 11201

D. Green, *Co-Chair*  
DuPont Central Science and Engineering (CS&E)  
Particle Science and Technology Center (PARSAT)  
Experimental Station, Building 304  
Wilmington, DE 19800-0304

Opening Remarks: A. Myerson

**Invited Paper: The Role of Plastic and Elastic Deformation of Crystals in the Particle Development Process** • 9:05 AM • *Paper No. 59a* • J.N. Sherwood, University of Strathclyde, Glasgow G1 1XL, Scotland, UK

**The Nucleation Kinetics of Paracetamol** • 9:35 AM • *Paper No. 59b* • B. Hendriksen\*, Lilly Research Centre, Surrey, GU20 6PH, UK, D. Grant (University of MN)

**Crystallization of Paracetamol** • 9:50 AM • *Paper No. 59c* • J.N. Sherwood\*, D.J.W. Grant, R.I. Ristic, B.Yu. Shekunov, University of Strathclyde, Glasgow G1 1XL, Scotland, UK

**The Effect of Polymeric Additives on the Crystallization of Phosphogypsum** • 10:05 AM • *Paper No. 59d* • B.M. Moudgil\*, S. Zhu, Y. Shishodia, University of Florida, Gainesville, FL

**Agglomeration Mechanisms in Al(OH)<sub>3</sub> Crystallization from Supersaturated Caustic Aluminate Solutions** • 10:20 AM • *Paper No. 59e* • D. Ilievski, E.T. White\*, University of Queensland, Brisbane, QLD 4072, AUSTRALIA

Break—10:35 AM

**The Dynamics of Supersaturated Sucrose Solutions** • 10:50 AM • *Paper No. 59f* • T.H. Lilley, D.J. Brown\*, University of Sheffield, Sheffield S1 4DU, UK

**Crystal Shape, The Role of Solvents and Impurities** • 11:05 AM • *Paper No. 59g* • A.S. Myerson\*, S.M. Jang, Polytechnic University, Brooklyn, NY

**Prediction and Control of Crystal Morphology** • 11:20 AM • *Paper No. 59h* • P. Meenan, D. Green\*, DuPont Central Science and Engineering (CS&E), Wilmington, DE

**Chemical and Structural Studies of the Crystallization of Organic Compounds by FT-Raman Spectroscopy** • 11:35 AM • *Paper No. 59i* • A. Brown\*, P. York, A.C. Williams, C. Doherty (Roche Products), University of Bradford, West Yorkshire BD7 1DP, UK

**Growth Anisotropy of Molecular Crystals** • 11:50 AM • *Paper No. 59j* • J.N. Sherwood\*, B. Yu. Shekunov, University of Strathclyde, Glasgow G1 1XL, Scotland, UK

Interim Remarks—12:05 AM

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Wednesday, August 17  
1:30-4:35 PM  
Colorado Ballroom J

## Crystallization & Precipitation II

Sponsored by the Particle Technology Forum

J.N. Sherwood, *Chair*  
University of Strathclyde  
Department of Pure and Applied Chemistry  
295 Cathedral Street  
Glasgow G1 1XL, Scotland UK

J. Rawlings, *Co-Chair*  
University of Texas  
Department of Chemical Engineering  
Austin, TX 78712

**Invited Paper: Model Identification and Control Strategies for Batch Crystallizers** • 1:30 PM • *Paper No. 60a* • J. Rawlings\*, S.M. Miller, H.B. Mathews, University of Texas, Austin, TX

**Precipitation of Barium Sulphate: Measurement of Sub micrometer Particle Sizes and Influence of Additives** • 2:00 PM • *Paper No. 60b* • B. Scarlett\*, M.A. van Drunen, H.G. Merkus, G.M. van Rosmalen, Delft University of Technology, 2600 GA Delft, THE NETHERLANDS

**Studies of Particle Growth by Means of In Situ Laser Interferometry** • 2:15 PM • *Paper No. 60c* • J.N. Sherwood\*, B. Yu. Shekunov, University of Strathclyde, Glasgow G1 1XL, Scotland, UK

**Control of Crystal Size Distribution of Ammonium Perchlorate using Two Stirred-Tanks in Series** • 2:30 PM • *Paper No. 60d* • C.Y. Tai\*, Cheng-yi Shih, C.W. Wong (Chung-Shan Inst.), National Taiwan University, Taipei, Taiwan, ROC

**A Novel Process for the Fabrication of Glaserite and Potassium Sulphate from Gypsum and Sylvinite in Aqueous Ammonia Solutions** • 2:45 PM • *Paper No. 60e* • J.A. Fernandez Lozano, University of Oriente, Estado, Anzoategui, VENEZUELA

Break—3:00 PM

**Crystallochemically Controlled Aggregation Processes—Twinning, Tectonics and Technology** • 3:15 PM • *Paper No. 60f* • R.J. Davey\*, J. Garside, B.R. Heywood (U. of Salford), UMIST, Manchester, M60 1QD, UK

**Double-Drawoff Crystallization-Industrial Applications** • 3:30 PM • *Paper No. 60g* • R. Kendall, DuPont Central Science and Engineering (CS&E), Newark, DE

**Optimization of Precipitation Crystallization with Respect to Subsequent Solid/Liquid Separation** • 3:45 PM • *Paper No. 60h* • D. Bellgardt\*, J. Weber, Dow Deutschland Inc., 21651 Stade, GERMANY

### Summary:

**SUMMARY PAPER: Crystallization & Precipitation** • 4:00 PM • *Paper No. 60i* • Prof. A. Myerson, Polytechnic University, Brooklyn, NY

Discussion & Concluding Remarks—4:30 PM

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Wednesday, August 17  
9:00-12:30 AM  
Colorado Ballroom I

## Fluidization & Transport Phenomena I

Sponsored by the Particle Technology Forum

L.S. Fan, *Chair*  
Ohio State University  
Dept. of Chemical Engineering  
140th W 19th Avenue  
Columbus, OH 43210

H. Arastoopour, *Co-Chair*  
Illinois Institute of Technology  
Dept. of Chemical Engineering  
Chicago, IL

Opening Remarks: L.S. Fan

**Invited Paper: Bubbleless Fluidization** • 9:05 AM • *Paper No. 61a* • M. Kwauk, Institute of Chemical Metallurgy, Beijing, 100080, CHINA

**Bubble Coalescence Mechanisms in Gas Fluidized Beds** • 9:35 AM • *Paper No. 61b* • J.G. Yates\*, D.J. Cheesman, University College London, Torrington Place, London WC1E 7JE, UK

**The Density of Fluidized Beds of FCC, and of a Group A/B Powder** • 9:50 AM • *Paper No. 61c* • Y. Xue, D. Geldart\*, H.Y. Xie, University of Bradford, Bradford, West Yorkshire, BD7 1DP, U.K.

**Analysis of Entrainment of the Particles to the Jet Zone in Fluidized Bed** • 10:05 AM • *Paper No. 61d* • H. Arastoopour\*, J. Li, S. Kim, Illinois Institute of Technology, Chicago, IL

**The Effect of System Pressure on Gas Fluidized Beds of Some Geldart Type Group B Powders** • 10:20 AM • *Paper No. 61e* • D. Newton\*, D. Johns, BP Chemicals Laboratory Sunbury, Sunbury-on-Thames, Middlesex TW16 7LL, ENGLAND

Break—10:35 AM

Visual Observations of Individual Particles in a Fluidized Bed • 10:50 AM • Paper No. 61f • G.P. Hartholt, A. Hoffmann, L. Janssen, University of Groningen, Nijenborgh 4, Groningen 9747AG, THE NETHERLANDS

Modeling of Gas-Solid Fluidized Beds by Taking into Account the Interparticle Forces • 11:05 AM • Paper No. 61g • J. Chaouki, R.B. Mahfoud, D. Klvana, Ecole Polytechnique, Montreal, QUEBEC, CANADA H3C 3A7

Interfacial Drag between Gas & Particles in Fast Fluidized Beds • 11:20 AM • Paper No. 61h • J.C. Chen, K. Tuzla, B. Herb (Air Products), Lehigh University, Bethlehem, PA

Three Dimensional Visualization to Gas Solid Suspension Flow in Circulating Fluidized Beds • 11:35 AM • Paper No. 61i • M. Horio, M. Tsukada, H. Kuroki, M. Ogasawara, H. Kamiya, Tokyo University of A & T, Tokyo 184, JAPAN

Wave Phenomena in Circulating Fluidized Beds • 11:50 AM • Paper No. 61j • E. Brue, R.J. Moore, C. Brown, Iowa State University, Ames, IA  
Interim Remarks—12:05 AM

[62] Wednesday, August 17  
1:30-4:35 PM  
Colorado Ballroom I

### Fluidization & Transport Phenomena II

Sponsored by the Particle Technology Forum

W.C. Yang, *Chair*  
Westinghouse  
Pittsburgh, PA

J.C. Chen, *Co-Chair*  
Lehigh University  
Dept. of Chemical Engineering  
Bethlehem, PA 18015

#### Opening Remarks

Invited Paper: Scale Up of Fluidized Bed Processes—Principles and Practice • 1:30 PM • Paper No. 62a • J.M. Matsen, Exxon Research & Engineering Company, USA

Evolution of Disturbances in Fluidized Beds • 2:00 PM • Paper No. 62b • S. Sundaresan, R. Jackson, Princeton University, Princeton, NJ

The Gas-Solids Fluidized Bed as a Spatio-Temporal Chaotic System • 2:15 PM • Paper No. 62c • M. L.M. Van der Stappen, J.C. Schouten, C.M. Van den Bleek, Delft University of Technology, 2628 BL Delft, THE NETHERLANDS

A Novel Fluidized-Bed Coating of Fine Particles by Rapid Expansion of Supercritical Fluid Solutions • 2:30 PM • Paper No. 62d • A. Tsutsumi, S. Nakamoto, T. Mineo, K. Yoshida, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113, JAPAN

Augmented Heat Transfer to a Moving Sphere in a Fluidized Bed • 2:45 PM • Paper No. 62e • C. Desai, G.M. Colver, Iowa State University, Ames, IA

Break—3:00 PM

Heat Transfer Between Fluidized Beds & Immersed Objects: Experimental and Model Analysis • 3:15 PM • Paper No. 62f • G. Ferrari, University of Salerno, 84084 Fisciano (SA), ITALY

Analysis of Random Behavior of Multiphase Flow in Gas-Liquid-Solid Fluidized Bed • 3:30 PM • Paper No. 62g • Y. Kang, M. Yashima, L.T. Fan, Kansas State University, Manhattan, KS

Surface Treatment of HDPE Powder by Oxygen Plasma in A Fluidized Bed Reactor • 3:45 PM • Paper No. 62h • S.D. Kim, S.H. Park, Korea Advanced Institute of Science and Technology, Taejon 305-701, JAPAN

#### Summary:

SUMMARY PAPER: Fluidization & Transport Phenomena • 4:00 PM • Paper No. 62i • Prof. L.S. Fan, Ohio State University, Columbus, OH

Discussion & Concluding Remarks—4:30 PM

Thursday, August 18  
8:00 AM-9:00 PM  
Colorado Ballroom E

### Plenary Lecture on Particle Technology and Materials: NANOPARTICLES BUILDING BLOCKS FOR ADVANCED MATERIALS

Dr. R.W. Siegel  
Argonne National Laboratory  
Materials Science Division  
Argonne, IL

[63] Thursday, August 18  
9:00 AM-12:30 PM  
Colorado Ballroom G

### Particle Interactions, Tribology & Assemblies I

Sponsored by the Particle Technology Forum

M. Tirrell, *Chair*  
University of Minnesota  
Department of Chemical Engineering  
151 Amundson Hall  
421 Washington Ave.  
Minneapolis, MN 55455-0132

J. Green, *Co-Chair*  
Agricultural Products  
DuPont Company  
Experimental Station, E402/1108  
Wilmington, DE 19880

Opening Remarks: M. Tirrell

Invited Paper: Experimental Studies on the Relation Between Adhesion and Friction • 9:05 AM • Paper No. 63a • J. Israelachvili, University of California, Santa Barbara, CA

Description of Bulk Friction in Terms of Effective Contact Interactions in Slow Shearing Flows of Granular Materials • 9:35 AM • Paper No. 63b • U. Tüzün, D. Heyes, University of Surrey, Guildford, Surrey GU2 5XH, UK

Oblique Impact of Elasto-Plastic Spheres • 9:50 AM • Paper No. 63c • C. Thornton, Z. Ning, Aston University, Birmingham B4 7ET, UK

Measurements of the Collision Properties of Small Spheres • 10:05 AM • Paper No. 63d • M. Louge, S. Foerster, Cornell University, Ithaca, NY

Mechanisms of Colloid Detachment in a Sonic Field • 10:20 AM • Paper No. 63e • M. Sharma, A. Tutuncu, The University of Texas at Austin, Austin, TX

Break—10:35 AM

The Electrostatic Field Around a Dielectric Particle Located Near a Conducting Plane • 10:50 AM • Paper No. 63f • T. Matsuyama, T. Yamamoto, Soka University, Hachioji Tokyo 192, JAPAN

An Electroacoustic and Rheological Investigation of a Coating Suspension of Fine Particles • 11:05 AM • Paper No. 63g • A. Dutta, P. Salvi, Osram Sylvania Inc., Danvers, MA

Electrokinetic Characterization of Attrition Particulates Derived from Zirconia-Silicate Milling Media • 11:20 AM • Paper No. 63h • R. Sharma, D. Czekaj, J. Texter, Eastman Kodak Company, Rochester, NY

Surface Characterization of Fine Powders • 11:35 AM • Paper No. 63i • J. Green, B. Ennis, DuPont Company, Wilmington, DE

Characterization of the Thermodynamic Surface Properties of Powders by Inverse Gas Chromatography • 11:50 AM • Paper No. 63j • M.D. Ticehurst, P. York & R.C. Rowe, University of Bradford, Bradford BD7 1DP, UK

Interim Remarks—12:05 AM

[64] Thursday, August 18  
1:30-4:35 PM  
Colorado Ballroom G

### Particle Interactions, Tribology & Assemblies II

Sponsored by the Particle Technology Forum

J. Israelachvili, *Chair*  
University of California  
Department of Chemical Engineering and  
Materials Department  
Santa Barbara, CA 93106

J.P.K. Seville, *Co-Chair*  
University of Surrey  
Department of Chemical Engineering  
Guildford, Surrey GU2 5XH UK

Invited Paper: Particle Interaction Laws and the Rheology of Assemblies • 1:30 PM • Paper No. 64a • B. Briscoe, Imperial College of Science, Technology and Medicine, London SW7 2BY, UK

Mechanical Properties of Particle Compacts • 2:00 PM • Paper No. 64b • J.P.K. Seville, M. Abdel-Ghani, R. Clift & M.J. Adams, University of Surrey, Guildford, Surrey GU2 5XH, UK

Effect of Particle Size Distribution on Porosity of Packed Particles • 2:15 PM • Paper No. 64c • A.B. Yu, R.P. Zou, N. Standish, D.L. Xu, University of New South Wales, Kensington, NSW, 2033, AUSTRALIA

Investigation on Porous Structures of Bulk Solids: Two Dimensional Simulation and Comparison with Real Material Systems • 2:30 PM • Paper No. 64d • M. Bottlinger, R. Kohlus, Deutsches Institut für Lebensmitteltechnik, 49610 Quakenbrück, GERMANY

Electrically Stimulated Agglomeration at an Earthed Surface • 2:45 PM • Paper No. 64e • C. Riehle, C. Wadenpohl, F. Löffler, Bayer A.G., D-51386 Leverkusen, GERMANY

Break—3:00 PM

The Electromechanical Valve for Solids • 3:15 PM • Paper No. 64f • M. Ghadiri, C. Martin, University of Surrey, Guildford, UK

Bubble Stability Modeling in Fluidized Beds Utilizing Electric Fields • 3:30 PM • Paper No. 64g • G.M. Colver, J.S. Yang, Iowa State University, Ames, IA

Hydrodynamic and Interparticle Forces in Gas Fluidized Beds • 3:45 PM • Paper No. 64h • H.Y. Xie, D. Geldart, University of Bradford, Bradford, West Yorkshire, BD7 1 DP, UK

Summary:

SUMMARY PAPER: Particle Interactions, Tribology & Assemblies • 4:00 PM • Paper No. 64i • Prof. M. Tirrell, University of Minnesota, Minneapolis, MN

Discussion & Concluding Remarks—4:30 PM

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Thursday, August 18  
9:00-12:30 AM  
Colorado Ballroom H

### Comminution & Attrition I

Sponsored by the Particle Technology Forum

D. Fuerstenau, *Chair*  
University of California-Berkeley  
Dept. of Materials Sci. & Mineral Engineering  
Hearst Mining Building  
Berkeley, CA 94720

S. G. Malghan, *Co-Chair*  
United States Department of Commerce  
National Institute of Standards and Technology  
Gaithersburg, MD 20899

Opening Remarks: D. Fuerstenau

Invited Paper: New Energy Law of Comminution in Ultra Fine Size Range • 9:05 AM • Paper No. 65a • G. Jimbo,\* Chubu Powtech Plaza Laboratory, Nagoya, 450, JAPAN

Measurement of Strain in a Brittle Particle During Impact Fracture • 9:35 AM • Paper No. 65b • R.P. King, Y. Zhu,\* University of Utah, Salt Lake City, UT

Pressure Distribution in a Highly Compacted Particle Bed • 9:50 AM • Paper No. 65c • K. Schönert,\* M. Kahle, Technische Universität Clausthal, 38658 Clausthal-Zellerfeld, GERMANY

A Rapid Method for Estimating Breakage Parameters Applied to the Comminution of Brittle Materials • 10:05 AM • Paper No. 65d • A. Raghen-Moayed, O. Trass,\* University of Toronto, Toronto, Ontario M5S 1A4, CANADA

Power Characteristics of Stirred Media Mills • 10:20 AM • Paper No. 65e • C. Harris, J. Zheng, P. Somasundaran,\* Columbia University, New York, NY  
Break—10:35 AM

Scale-Up of Chemical Processes Involving Agitator Media Mills • 10:50 AM • Paper No. 65f • Q.Q. Zhao,\* J.W. LaPorte, J.M. Leithen, J.J. Harrington, DuPont Central Research and Development, Wilmington, DE

Evaluation of Energy Efficiency of New Comminution Devices • 11:05 AM • Paper No. 65g • Y.C. Lo,\* Control International, Inc., Salt Lake City, UT

Ultrafine Grinding in a Two Stage Rotor Impact Mill • 11:20 AM • Paper No. 65h • K. Leschonski,\* R. Drögemeier, Technische Universität Clausthal, D-3392 Clausthal-Zellerfeld, GERMANY

An Assessment of Repeatability in the Milling of Silicon Nitride Powders in a High Energy Agitation Ball Mill • 11:35 AM • Paper No. 65i • S.G. Malghan,\* D.B. Minor, P.T. Pei, S. Schiller, United States Department of Commerce, Gaithersburg, MD

Effect of Dry Grinding of Mixture on Preparation of Cordierite Ceramics and their Dielectric Properties • 11:50 AM • Paper No. 65j • J.M. Filio, K. Sugiyama, E. Kasai, F. Saito,\* Tohoku University, Katahira, Aoba-ku, Sendai 980, JAPAN

Interim Remarks—12:05 AM

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Thursday, August 18  
1:30-4:35 PM  
Colorado Ballroom H

### Comminution & Attrition II

Sponsored by the Particle Technology Forum

K. Schönert, *Chair*  
Technische Universität Clausthal  
Institut für Aufbereitung von Rohstoffen  
und Reststoffen  
Walther Nemat Straße 9  
38678 Clausthal-Zellerfeld, GERMANY

PTF-7

M. Ghadiri, *Co-Chair*  
University of Surrey  
Department of Chemical and Process Engineering  
Guildford, Surrey GU2 5XH UK

Invited Paper: Spark Erosion—A Versatile Particle Technology • 1:30 PM • Paper No. 66a • A.E. Berkowitz,\* R.H. Kodama, F.E. Spada, University of California, San Diego, La Jolla, CA

Energy-Size Reduction Laws for Ultrasonic Fragmentation • 2:00 PM • Paper No. 66b • S. Pratsinis,\* K.A. Kusters, S.G. Thoma (U. of NM), D. Smith (U. of NM), University of Cincinnati, Cincinnati, OH

Computer Simulation of Particle Breakage • 5:30 PM • Paper No. 66c • A.V. Potapov,\* C.S. Campbell, University of Southern California, University Park, Los Angeles, CA

Measurement of Particle Material Properties and their Relation to Attrition Phenomena in Solids Handling • 2:30 PM • Paper No. 66d • L. Johnsson,\* B. Ennis (DuPont), Swiss Federal Institute of Technology, CH-8952 Schlieren, Zurich, SWITZERLAND

Agglomerate Fracture/Fragmentation • 2:45 PM • Paper No. 66e • C. Thornton, K.D. Kafufi,\* Aston University, Birmingham B4 7ET, UK

Break—3:00 PM

Attrition Evaluation for Catalysts Used in Fluidized or Circulating Bed Reactors • 3:15 PM • Paper No. 66f • G. Dessalces, F. Kolenda,\* J.P. Reymond, Unite Mixte IFP-CNRS, 69390 Vernaison, FRANCE

Investigation of Breakage and Classification in a Fluidized Bed Opposed Jet Mill • 5:30 PM • Paper No. 66g • H. Berthiaux, J.A. Dodds,\* Laboratoire des Science du Génie Chimique, 54001 Nancy, FRANCE

The Dynamic Modeling of a Closed Loop Jet Mill System • 3:45 PM • Paper No. 66h • H.J.C. Gommeren,\* D. Heitzmann, H. Kramer, B. Scarlett, Delft University of Technology, Leeghwaterstr. 44. 2628 CA, Delft, THE NETHERLANDS

Summary:

SUMMARY PAPER: Comminution & Attrition • 4:00 PM • Paper No. 66i • Prof. D. Fuerstenau,\* University of California-Berkeley, Berkeley, CA

Discussion & Concluding Remarks—4:30 PM

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Thursday, August 18  
9:00-12:30 AM  
Colorado Ballroom I

### Particle Formation in Gases I

Sponsored by the Particle Technology Forum

S. Pratsinis, *Chair*  
University of Cincinnati  
Department of Chemical Engineering  
Cincinnati, OH 45221-0171

M. Sadakata, *Co-Chair*  
University of Tokyo  
Dept. of Chemical Engineering  
Bunkyo-ku, Tokyo 113 JAPAN

Opening Remarks: S. Pratsinis

Invited Paper: The Birth of Nanometer Agglomerate Structures From the Gas Phase • 9:05 AM • Paper No. 67a • S. Friedlander, UCLA, Los Angeles, CA

Invited Paper: Systematic Approach to Design of Reactor for Production of Ultra Fine Particles • 9:35 AM • Paper No. 67b • M. Sadakata, University of Tokyo, Bunkyo-ku, Tokyo 113, JAPAN

Mixing and Turbulent Effects on TiO2 Particle Formation and Growth • 10:05 AM • Paper No. 67c • P.A. Strakey,\* L.R. Collins, R.J. Santoro, The Pennsylvania State University, University Park, PA

Effect of Dopants in the Flame Synthesis of Titania • 10:20 AM • Paper No. 67d • S. Pratsinis,\* S. Vemury, University of Cincinnati, Cincinnati, OH

Break—10:35 AM

Growth Mechanisms of Particles Synthesized in a Flame • 10:50 AM • Paper No. 67e • T. Araki,\* T. Ono, M. Matsukata, K. Ueyama, R. Oshima, Osaka University, Toyonaka-shi, Osaka 560, JAPAN

Visualization of Ultra Fine Particles Formation Process by the Ar-H2 Arc Plasma Method • 11:05 AM • Paper No. 67f • K. Saitou, Gunma University, Kiryu, 376 Gunma, JAPAN

Particle Growth Mechanism of Aluminum Nitride Prepared by Chemical Vapor Deposition Method • 11:20 AM • Paper No. 67g • H.J. Kim,\* Y. Egashira, H. Komiyama, M. Sadakata, University of Tokyo, Bunkyo-ku, Tokyo 113, JAPAN

Particle Agglomeration by Thermophoresis with Particle Input Sources • 11:35 AM • Paper No. 67h • D. Yang, The University of Tennessee Space Institute, Tullahoma, TN

Effects of Fuel-Lubricating Oil Combustion on the Particulate Emissions from Diesel Engine • 11:50 AM • Paper No. 67i • A. Macias-Machin,\* V. Henriquez, J.Lopez Cancio, A. Vera, E.T.S.I.I. de Las Palmas, 35017 Las Palmas de Gran Canaria, SPAIN.  
Interim Remarks—12:05 AM

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Thursday, August 18  
1:30-4:35 PM  
Colorado Ballroom I

### Particle Formation in Gases II

Sponsored by the Particle Technology Forum

S. Pratsinis, *Chair*  
University of Cincinnati  
Department of Chemical Engineering  
Cincinnati, OH 45221-0171

H. Sauter, *Co-Chair*  
Kernforschungszentrum Karlsruhe GmbH  
L A F I  
Weberstraße 5  
Postfach 3640  
D-76021, Karlsruhe GERMANY

Invited Paper: Synthesis of Powders from Solution Aerosols • 1:30 PM • Paper No. 68a • G.L. Messing,\* S.C. Zhang, R. Selvaraj, Pennsylvania State University, University Park, PA

Effect of Reactor Atmosphere on Characteristics of Fine Particles Prepared by Spray Pyrolysis Method • 2:00 PM • Paper No. 68b • S. Deguchi,\* N. Kobayashi, H. Matsuda, M. Hasatani, Nagoya University, Furo-cho Chikusa-ku, Nagoya 464-01, JAPAN

Nanoparticle Generation in Supersonic Free Jets • 2:15 PM • Paper No. 68c • C.T. Crowe,\* K. Recknagel, J.N. Chung, Washington State University, Pullman, W

Effects of Total Pressure in Continuous Flow Condensation Aerosol Generator • 2:30 PM • Paper No. 68d • S.S. Kim,\* Y.K. Kim, Korea Advanced Institute of Science and Technology, Taejeon 305-701, KOREA

Synthesis of Non-Crystalline Spherical Particles by Gas-Phase Hydrolysis of Aerosol Liquid-Droplets • 2:45 PM • Paper No. 68e • G.P. Martins,\* J-G. Pradell, Colorado School of Mines, Golden, CO

Break—3:00 PM

Experimental Investigation of the Formation of Particles by Desublimation • 3:15 PM • Paper No. 68f • M. Kodde,\* D. Mewes, Institut für Verfahrenstechnik, 30167 Hannover, GERMANY  
Combustion Synthesis of TiB2 Powders • 3:30 PM • Paper No. 68g • D.W. Readey,\* C.H. Lantz, J.J. Moo, The Colorado School of Mines, Golden, CO

'Additive Time' Treatment of Data on the Speed of Chemical Reaction Fronts in Reactive Powders—e.g., Combustion Synthesis of TiB<sub>2</sub>(s) • 3:45 PM • Paper No. 68h • D.E. Rosner, Yale University, New Haven, CT

Summary:

**SUMMARY PAPER: Particle Formation in Gases** • 4:00 PM • Paper No. 68i • Prof. S. Pratsinis, University of Cincinnati, Cincinnati, OH

Discussion & Concluding Remarks—4:30 PM

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Thursday, August 18

9:00-12:30 AM

Colorado Ballroom J

### Multiphase Flow I

Sponsored by the Particle Technology Forum

M. Roco, Chair

National Science Foundation  
Engineering Directorate  
Arlington, VA

M.L. Hunt, Co-Chair

California Institute of Tech.  
Division of Engineering & Applied Science  
Pasadena, CA 91125

Opening Remarks: M. Roco

Invited Paper: Interrogation of Direct Numerical Simulation of Fluid Particle Motion • 9:05 AM • Paper No. 69a • D. Joseph\*, University of Minnesota, Minneapolis, MN

Simulation of Microstructure Evolution with Parallel Virtual Machine (PVM) • 9:35 AM • Paper No. 69b • N. Phan-Thien (U. of Sydney), S. Kim\*, University of Wisconsin, Madison, WI

Hopper Flows observed with a Cellular Automaton for Granular Media • 9:50 AM • Paper No. 69c • D. Deserable\*, J. Martinez, S. Masson, INSA Campus de Beaulieu, FRANCE

Collisional Interactions in Multiphase Flow • 10:05 AM • Paper No. 69d • J.T. Jenkins\*, Cornell University, Ithaca, NY

The Role of Particle Size and Shape in the Propagation of Reaction in Explosive and Pyrotechnic Formulations • 10:20 AM • Paper No. 69e • J.L. Austing\*, A.J. Tullis, R. Pape, R.G. Draftz, D. Gidaspow, IIT Research Institute, Chicago, IL

Break—10:35 AM

Invited Paper: Discrete Particle Simulations of Multiphase Flows • 10:50 AM • Paper No. 69f • Y. Tsuji\*, Osaka University, Osaka 565, JAPAN

Transient Heat Transfer in an Amorphous Particle with Applications to Fusible Toner • 11:20 AM • Paper No. 69g • M.L. Hunt\*, T. Mitsuya, California Institute of Tech., Pasadena, CA

Studies of Multiphase Flow by Nuclear Magnetic Resonance Imaging • 11:35 AM • Paper No. 69h • E. Fukushima\*, S.A. Altobelli, A. Caprihan, E.K. Jeong, M. Nakagawa, The Lovelace Institutes, Albuquerque, NM

Density Gradient Measurements in the Three Phase Flow of Air Sparged Hydrocyclone Flotation • 11:50 AM • Paper No. 69i • J.D. Miller\*, A. Das, University of Utah, Salt Lake City, UT

Interim Remarks—12:05 AM

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Thursday, August 18

1:30-4:35 PM

Colorado Ballroom J

### Multiphase Flow II

Sponsored by the Particle Technology Forum

D. Joseph, Chair

University of Minnesota  
Dept. of Aerospace Engineering & Mechanics  
107 Akerman Hall, 110 Union Street  
Minneapolis, MN 55455

M. Sommerfeld, Co-Chair

Universität Erlangen/Nürnberg  
Lehrstuhl für Strömungsmechanik  
Gauerstr. 5, 91058 Erlangen GERMANY

Invited Paper: Shear-Induced Particle Diffusion and its Effect on the Viscometry of Concentrated Suspensions • 1:30 PM • Paper No. 70a •

A. Acrivos\*, City College of CUNY, New York, NY

Characterization of Particulate Systems by Phase-Doppler Anemometry • 2:00 PM • Paper No. 70b •

M. Sommerfeld\*, H.-H. Qiu, Universität Erlangen/Nürnberg, 91058 Erlangen, GERMANY

Measurement of Particle Dispersion Coefficients Using Electrical Impedance Tomography • 2:15 PM •

Paper No. 70c • G.J. Grootveld\*, B. Scarlett, G. Van Weert, Delft University of Technology, 2600 GA Delft, THE NETHERLANDS

Structure and Rheology Relations in Colloidal Suspensions • 2:30 PM • Paper No. 70d •

N.J. Wagner\*, University of Delaware, Newark, DE

Movement of Micron Size Particles Due to Diffusion and Thermal Forces • 2:45 PM • Paper

No. 70e • H. Schäfer\*, D. Mewes, Institut für Verfahrenstechnik, 30167 Hannover, GERMANY

Break—3:00 PM

Micro-and Macrostructure of Particle-Liquid Flow in a Centrifugal Pump • 3:15 PM • Paper No. 70f •

M. Roco\*, T. Cader, NSF, Arlington, VA

Multiphase Flows in the Processing and Manufacturing Industries • 3:30 PM • Paper

No. 70g • C.T. Crowe\*, Washington State University, Pullman, WA

Drag Analysis on Cylindrical Particles Through the Orifice of a Super-sonic Jet Expansion • 3:45 PM •

Paper No. 70h • G.S. Holderbaum\*, J.H. Saunders, C.A. Alexander, Battelle, Columbus, OH

Summary:

Summary Paper: Multiphase Flow • 4:00 PM •

Paper No. 70i • Dr. M. Roco\*, National Science Foundation, Arlington, VA

Discussion & Concluding Remarks—4:30 PM

Friday, August 19

8:00 AM-9:00 PM

Colorado Ballroom E

### Plenary Lecture on Particle Technology and Manufacturing

Dr. O. Richmond

Alcoa Technical Center  
100 Technical Drive  
Alcoa Center, PA 15069

[71]

Friday, August 19

9:00-12:30 AM

Colorado Ballroom G

### Powder Mechanics & Material Storage I

Sponsored by the Particle Technology Forum

J. Carson, Chair  
Jenike & Johanson, Inc.

1 Technology Drive  
Westford, MA 01886

U. Tüzün, Co-Chair  
University of Surrey

Department of Chemical & Process Engineering  
Guildford, Surrey UK

Opening Remarks: J. Carson

Invited Paper: Measurement of Flow Properties of Bulk Solids • 9:05 AM • Paper No. 71a • J. Schwedes, Tech. Universität Braunschweig, 3300 Braunschweig, GERMANY

A New Ring Shear Tester for Flowability and Time Consolidation Measurements • 9:35 AM • Paper No. 71b • D. Schulze, Schwedes & Schulze Schüttguttechnik, Consultants, D-38106 Braunschweig, GERMANY

Particle Properties Leading to Stick-Slip Behaviour of Compacted Powders in Shear Testers • 9:50 AM • Paper No. 71c • M. van der Kraan\*, W.J. Scholten, B. Scarlett, Delft University of Technology, 2600 GA Delft, THE NETHERLANDS

Micromechanics of General 3D Shear Deformation • 10:05 AM • Paper No. 71d • C. Thornton, G. Sun\*, Aston University, Birmingham B4 7ET, UK

The Single Particle Equivalent Concept (SPE), The Physical Model of Particle Interaction Constituting Assembly Behaviour • 10:20 AM • Paper No. 71e • N.W.A. Broug, 2741 AN Waddinxveen, THE NETHERLANDS

Break—10:35 AM

Parameter Determination and Model Verification for Constitutive Equations Applied to Cohesive Food Powders • 10:50 AM • Paper No. 71f •

M.A. Tripodi\*, V.M. Puri, H.B. Manbeck, The Pennsylvania State University, University Park, PA

Constitutive Model Development for Fine Cohesive Food Powders Using Cubical Triaxial Cell •

11:05 AM • Paper No. 71g • S. Kamath\*, V.M. Puri, H.B. Manbeck, The Pennsylvania State University, University Park, PA

Mechanical Characteristics of Brittle Crumbly Particulates Tested Individually and in Bulk •

11:20 AM • Paper No. 71h • R. Nixon, D. Ulbricht, C. Nuebel, N. Wollney & M.D. Normand, M. Peleg\*, University of Massachusetts, Amherst, MA

The Measurement and Characterization of Powder Flow Properties at Elevated Temperature •

11:35 AM • Paper No. 71i • H.O. Kono\*, E. Aksoy, West Virginia University, Morgantown, WV

Measurement of Caking of Crystalline Solids •

11:50 AM • Paper No. 71j • T. Bell\*, R. Davies, B. Ennis, DuPont Company, Wilmington, DE

Interim Remarks—12:05 AM

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Friday, August 19

1:30-4:35 PM

Colorado Ballroom G

### Powder Mechanics & Material Storage II

Sponsored by the Particle Technology Forum

V. Puri, Chair

The Pennsylvania State University  
Department of Agricultural and  
Biological Engineering  
University Park, PA 16802

J. Schwedes, Co-Chair

Tech. University Braunschweig  
Institute für Mechanische Verfahrenstechnik  
Volkmaroder Strasse 4-5  
3300 Braunschweig GERMANY

Invented Paper • 1:30 PM • Paper No. 72a • A. Roberts, University of Newcastle, AUSTRALIA  
Recent Developments in Rotary Feeders • 2:00 PM • Paper No. 72b • W. Krambrock, H. Wilms,\* Zeppelin Schüttguttechnik GmbH, D-88250 Weingarten, GERMANY

Fluidization Techniques for Discharging Fine Powders from Bins and Silos • 2:15 PM • Paper No. 72c • D.J. Goodwill,\* R.T. Jenkyn, T.A. Royal, Jenike & Johanson Ltd., Etobicoke, ONTARIO M9W 5X9, CANADA

Flow Rate from Slot Flow Relationships: A Promising Approach to the Metering of Particulate Solids • 2:30 PM • Paper No. 72d • C.E. Davies, Industrial Research Limited, NEW ZEALAND

Predicting the Behaviour of Industrial Powders in Precision Handling Equipment • 2:45 PM • Paper No. 72e • A.C. Hoffmann,\* R.J. Finkers, University of Groningen, 9747 AG Groningen, J.A. Seegers, CALUMATIC B.V., Dongen, THE NETHERLANDS

Break—3:00 PM

Load Measurements on Silos: Influence of the Own Stiffness of the Measuring Instrument on the Results • 3:15 PM • Paper No. 72f • G. Haaker,\* C.A. Laan, Universiteit Twente, 7500 AE Enschede, THE NETHERLANDS

Quality Assurance in Storage, Blending and Handling • 3:30 PM • Paper No. 72g • W. Krambrock H. Wilms,\* Zeppelin Schüttguttechnik GmbH, D-88250 Weingarten, GERMANY

Particle Properties that Control the Flowability of Powders: A Case Study for a Pesticide Product • 3:34 PM • Paper No. 72h • J. Jariwala, G. Sunshine, B. Ennis, J. Green, DuPont Company, Wilmington, DE

Summary Paper: Powder Mechanics & Material Storage • 4:00 PM • Paper No. 72i • J. Carson, Jenike & Johanson, Inc., Westford, MA

Discussion & Concluding Remarks—4:30 PM

**[73]** Friday, August 19  
9:00-12:30 AM  
Colorado Ballroom H

### Particle Modification & New Processes I

Sponsored by the Particle Technology Forum

D.J. Grant, *Chair*  
University of Minnesota  
College of Pharmacy  
308 Harvard Street  
Minneapolis, MN 55455

M. Senna, *Co-Chair*  
Keio University  
Faculty of Science and Technology  
3-14-1 Hiyoshi

Kohoku-ku, Yokohama 22381-45-563-1141 JAPAN

Opening Remarks: D.J. Grant

Invited Paper: Modification of Chemical Properties of Solids by Their Mechanical Activation • 9:05 AM • Paper No. 73a • V. Boldyrev, Institute of Solid State Chemistry, Novosibirsk, 91 630091, RUSSIA

Mechanochemical Technology of Synthesis of the Refractory Compounds and Alloys Based Upon Them • 9:35 AM • Paper No. 73b • A.A. Popovich,\* V.P. Reva, V.N. Vasilenko, T.A. Popovich, Far Eastern State Technic University, Vladivostok 690600, RUSSIA

Mechanical Activation Influence on the Formation of Structure and Phase Composition of Sintered Ceramics from Titanium Diboride • 9:50 AM • Paper No. 73c • O.G. Terekhova, O.K. Lepakora, Structural Macrokinetics Institute RAN, RUSSIA

Mechanisms and Technology of Soft Mechanochemical Synthesis of Complex Silicates and Related Compounds • 10:05 AM • Paper No. 73d • M. Senna,\* J.F. Liao, T. Watanabe, K. Gomi, Keio University, Kohoku-ku, Yokohama 22381-45-563-1141, JAPAN

The Properties of Drugs and Polymers after their Mechanical Treatment • 10:20 AM • Paper No. 73e • S.S. Khalikov,\* E. Kristallovich, M. Khodjaeva, M. Turakhodjaev, N. Abdullaev, Kh. Aripov, E. Pereverzeva, A. Karimov, U. Musaev, V. Boldyrev, V. Dooshkin, T. Shakhtshneider, Institute of Plant Chemistry Substances & Acad. of Sci. Uzbekistan, TASHKENT

Break—10:35 AM

Mechanical Property Modification of Powder • 10:50 AM • Paper No. 73f • C.M. Sinko,\* G.T. Carlson, B.A. Beckwith, Pfizer Central Research, Groton, CT

Contribution to the Tribomechanical Activation of Abu Tartur Egyptian Raw Phosphates • 11:05 AM • Paper No. 73g • S.S. Ibrahim, M.A. Youssef,\* Central Metallurgical R&D Institute, Cairo, EGYPT

A Novel Particles Composer and Its Performance Evaluation • 11:20 AM • Paper No. 73h • K. Miyanami,\* M. Satoh, T. Yoshida, University of Osaka Prefecture, Sakai, 593, T. Tanimoto, Tokuju Corp. JAPAN

Chemical Reactions During the ThO<sub>2</sub> and ThO<sub>2</sub>-UO<sub>2</sub> Fuel Fabrication • 11:35 AM • Paper No. 73i • J.C. Clayton, Westinghouse Electric Corporation, West Mifflin, PA

Microwave Decomposition of Solvent Treated Boehmite as a Precursor for Fine Alumina Particulates • 11:50 AM • Paper No. 73j • T.V. Mani,\* P. Krishna-Pillai, A.O. Damodaran, K.G.K. Warrior, Regional Research Laboratory (CSIR), Trivandrum-695019, INDIA

Interim Remarks—12:05 AM

**[74]** Friday, August 19  
1:30-4:35 PM  
Colorado Ballroom H

### Particle Modification & New Processes II

Sponsored by the Particle Technology Forum

V. Boldyrev, *Chair*  
Institute of Solid State Chemistry  
Sib. Branch Acad. Sci.  
Derzhavina, 18  
Novosibirsk, 91 630091 RUSSIA

C.M. Sinko, *Co-Chair*  
Pfizer Inc.  
Pharmaceutical R&D, Central Research Division  
Eastern Point Road  
Groton, CT 06340

Invited Paper: Establishment of Guidelines for Better Ceramics through Novel Examination of Features in Ceramic Processing • 1:30 PM • Paper No. 74a • K. Uematsu, Nagoaka University of Technology, Kamitomioka, Nagoaka, Niigata, JAPAN

Synthesis of Magnetic Particles and Superconductors Using Microemulsions • 2:00 PM • Paper No. 74b • V. Pillai,\* P. Kumar, D.O. Shah, University of Florida, Gainesville, FL

Preparation of Fine Perovskite Powders by Freeze-Drying • 2:15 PM • Paper No. 74c • J. Kirchnerova,\* D. Klvana, Ecole Polytechnique, Montreal H3C 3A7, CANADA

Recrystallization Using Supercritical Fluids: Novel Techniques for Particle Modification • 2:30 PM • Paper No. 74d • P. Gallagher-Wetmore,\* M. Coffey, V. Krukonic, Phasex Corporation, Lawrence, MA

Micromorphology and Surface Geometry of Particulate Solids in the Drug Development Process • 2:45 PM • Paper No. 74e • R. Tawashi,\* M. Akbarieth, University of Montreal, Montreal, PQ H3C-317, CANADA

Break—3:00 PM

Shape Modification of Drug Particle by Crystallisation • 3:15 PM • Paper No. 74f • H.K. Chan,\* I. Gorda, Genentech, Inc., S. San Francisco, CA 94080, USA

Consequences of Interfacial Phenomena on the Crystallization and Dissolution of Organic Crystals • 3:30 PM • Paper No. 74g • N. Rodriguez-Hornedo, University of Michigan, Ann Arbor, MI

Microcalorimetric Investigation of Moisture-Mediated Phase-Transitions in Some Pharmaceutical Solids • 3:45 PM • Paper No. 74h • S.P. Duddu,\* M.E. Morris, N.G. Das, S.M. Milosovich, T.D. Sokolowski, SmithKline Beecham Pharmaceuticals, King of Prussia, PA

Summary:

Summary Paper: Particle Modification & New Processes • 4:00 PM • Paper No. 74i • Prof. D.J. Grant, University of Minnesota, Minneapolis, MN

Discussion & Concluding Remarks—4:30 PM

**[75]** Friday, August 19  
9:00-12:30 AM  
Colorado Ballroom I

### Dispersion, Rheology & Mixing I

Sponsored by the Particle Technology Forum

P. Somasundaran, *Chair*  
Columbia University  
Henry Krumb School of Mines  
New York, NY

J. Raper, *Co-Chair*  
School of Chemical Engineering & Industrial Chemistry  
UNSW  
P.O. Box 1  
Kensington, NSW 2033 AUSTRALIA

Opening Remarks: P. Somasundaran

Invited Paper: Particle Interactions in Concentrated Dispersions as Probed by the Capillary Force Balance • 9:05 AM • Paper No. 75a • D. Wasan,\* A.D. Nikolov, Illinois Institute of Technology, Chicago, IL

Stabilization Mechanisms of Oxide Dispersions in Non-Aqueous Media • 9:35 AM • Paper No. 75b • S. Krishnakumar,\* X. Yu, P. Somasundaran, Henry Krumb School, Columbia University, New York, NY

Beneficiation of High MgO Phosphate Rock by Selective Flocculation • 9:50 AM • Paper No. 75c • S. Mathur, T. Prakash, B.M. Moudgil,\* University of Florida, Gainesville, FL

Comparative Studies on the Adsorption of AOT and CTAB Surfactants on Flourite Minerals • 10:05 AM • Paper No. 75d • A. Yehia,\* A. Ateya, B.G. Ateya, Central Metallurgical R&D Institute, Cairo, EGYPT

The Impact of Different Flocculation Conditions on the Flocculation Mechanism of Kaolinite with Alum and the Dewatering Ability • 10:20 AM • Paper No. 75e • K. Ng, R. Amal,\* J. Raper, T.D. Waite, University of New South Wales, Kensington, New South Wales 2033, AUSTRALIA

Break—10:35 AM

Aggregation of Titania to Form Ceramic Membrane • 10:50 AM • Paper No. 75f • R.B. Hutchison,\* J. Raper, Univ. of New South Wales, Kensington, NSW 2033, AUSTRALIA

**Magnetic Flocculation of Paramagnetic Particles • 11:05 AM • Paper No. 75g • C. Tsouris; T.C. Scott, Oak Ridge National Laboratory, Oakridge, TN**

**Direct Measurement of Floc Breakage in Flowing Suspensions • 11:20 AM • Paper No. 75h • S.J. Peng; R.A. Williams, University of Exeter, Pool, Cornwall TR15 3SE, UK**

**Experimental Investigation of Coal Flotation in a Weir Flotation Centrifuge • 11:35 AM • Paper No. 75i • K. Leschonski; H. Schmidthals, Technische Universität Clausthal, 38678 Clausthal-Zellerfeld, GERMANY**

**Steel Sludge Dewatering for Environmentally Sound Resource Recycling • 11:50 AM • Paper No. 75j • S.A. Shuey; W. Tolley, United States Bureau of Mines, Salt Lake City, UT, B. Brown, Idaho Nat. Eng. Lab., ID**

*Interim Remarks—12:05 AM*

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**Friday, August 19  
1:30-4:35 PM  
Colorado Ballroom I**

**Dispersion, Rheology & Mixing II**

**Sponsored by the Particle Technology Forum**

**N.J. Wagner, Chair**  
University of Delaware  
Newark, DE 19716

**B. M. Moudgil, Co-Chair**  
University of Florida

Department of Materials Science and Engineering  
161 Rhines Hall  
Gainesville, FL 32611-2066

**Invited Paper: Designing Stable Colloidal Dispersions with Controlled Flow Properties • 1:30 PM • Paper No. 76a • J. Mewis, K.U. Leuven, B-3001 Heverlee (Leuven), BELGIUM**

**Dispersion Efficiency and Rheology of Sterically Stabilized Colloidal Silica • 2:00 PM • Paper No. 76b • A. Merrington; Z. Yang, D. Meier, Michigan Molecular Institute, Midland, MI**

**Determination of Changes in Rheological Properties of Mineral Slurries • 2:15 PM • Paper No. 76c • S.K. Kawatra; A.K. Bakshi, Michigan Technological University, Houghton, MI**

**Modification of Oxide Ceramic Slurries by an In Situ Sol Precipitation Method • 2:30 PM • Paper No. 76d • M. Senna; H. Shigetani, T. Kayukawa, Keio University, Kohoku-ku, Yokohama 223, JAPAN**

**Rheology of Colloid Laden Interfaces: Influence of Interparticle Interactions • 2:45 PM • Paper No. 76e • D.E. Tambe; M. Sharma, The University of Texas at Austin, Austin, TX**

*Break—3:00 PM*

**Microdeformation and Rheology of Hydrogel Particles • 3:15 PM • Paper No. 76f • D. Andrei, B.J. Briscoe, P.F. Luckham, D. Williams; Imperial College of Science, Technology and Medicine, London SW7 2BY, UK**

**Particle Flocculation in Sheared Suspensions • 3:30 PM • Paper No. 76g • P. Spicer, S. Pratsinis; University of Cincinnati, Cincinnati, OH**

**Study on Mechanical Agitation for Particles Dispersion in Liquid Media • 3:45 PM • Paper No. 76h • S. Lu; J. Guo, University of Science and Technology Beijing, Beijing, CHINA**

*Summary:*

**Summary Paper: Dispersions, Rheology & Mixing • 4:00 PM • Paper No. 76i • Prof. P. Somasundaran, Columbia University, New York, NY**

*Discussion & Concluding Remarks—4:30 PM*

**[77]**

**Friday, August 19  
9:00-12:30 AM  
Colorado Ballroom J**

**Solids Transport, Separation & Classification I**

**Sponsored by the Particle Technology Forum**

**S. Savage, Chair**  
McGill University  
Dept. of Mechanical Engineering  
Montreal, Quebec, H3A 2A7 CANADA

**R. Clift, Co-Chair**  
University of Surrey  
Centre for Environmental Strategy  
Department of Chemical Engineering  
Guildford, Surrey GU2 5XHUK

*Opening Remarks: S. Savage & B. Pfeffer*

**Invited Paper: Raining, Slipping and Stationary Granular Beds in Rapidly Rotating Horizontal Drums—A Numerical Analysis • 9:05 AM • Paper No. 77a • O. Walton, Lawrence Livermore National Laboratory, Livermore, CA**

**Experimental Studies of Vibrational Size Segregation • 9:35 AM • Paper No. 77b • A.D. Rosato; R.N. Dave, New Jersey Institute of Technology, Newark, NJ**

**Thermal Relaxation Behind Pressure Waves in Granular Flow • 9:50 AM • Paper No. 77c • T. Astarita, R. Ocone; G. Astarita, Università di Napoli, "Federico II", Napoli, ITALY**

**On the Observed Instabilities in Granular Flows in Rotating Cylinders • 10:05 AM • Paper No. 77d • A.A. Boateng; P.V. Barr, Swarthmore College, Swarthmore, PA**

**Continuous Powder Mixing • 10:20 AM • Paper No. 77e • K. Sommer, Tech. Universität München, Freising-Weihenstephan, GERMANY**

*Break—10:35 AM*

**The Interaction of Feeding Constancy and Residence Time Distribution in Continuous Particulate Mixing Processes—the Variance Reduction Ratio • 10:50 AM • Paper No. 77f • R. Weinekötter; L. Reh, ETH Zürich, Institute for Process and Cryogenic Engineering, SWITZERLAND**

**Particle Mixing Process Systems • 11:05 AM • Paper No. 77g • T. Taylor, Unilever Research, Bebington, Wirral, Merseyside, UK**

**Wet Counterflow Microfine Classification in a Centrifuge • 11:20 AM • Paper No. 77h • K. Schönert; C. Priesmann, Technische Universität Clausthal, 38678 Clausthal-Zellerfeld, GERMANY**

**Classification of Concentrated Suspensions Using Inclined Settlers • 11:35 AM • Paper No. 77i • H. Geocol, R.H. Davis; University of Colorado at Boulder, Boulder, CO**

**Batch and Continuous Sedimentation under Inclined Surfaces • 11:50 AM • Paper No. 77j • A.S. Ward; P.H. Poh, D.J. Brown, Loughborough University of Technology, Loughborough, Leeds, LE11 3TU, UK**

*Interim Remarks—12:05 AM*

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**Friday, August 19  
1:30-4:35 PM  
Colorado Ballroom J**

**Solids Transport, Separation & Classification II**

**Sponsored by the Particle Technology Forum**

**B. Pfeffer, Chair**  
New Jersey Institute of Technology  
University Heights  
Newark, NJ USA

**G.E. Klinzing, Co-Chair**  
University of Pittsburgh  
Dept. of Mechanical Engineering  
Pittsburgh, PA 15261

**Invited Paper: An Overview of Solids Transport • 1:30 PM • Paper No. 78a • O. Molerus, University Erlangen-Nürnberg, Erlangen, GERMANY**

**Numerical Simulation of Porous Plate Classifier • 2:00 PM • Paper No. 78b • J.W. Gentry; J.R. Wu, J. Gebhart, G. Scheuch, University of Maryland, College Park, MD**

**Use of Centrifugal Air Classification in the Grading of Dolomitic Limestone for Modeling Hydrocyclone Operation • 2:15 PM • Paper No. 78c • E. Ortega-Rivas; L. Svarovsky, University of Chihuahua, Chihuahua, MEXICO**

**Classification in an Impeller Wheel Classifier and its Limits of Application • 2:30 PM • Paper No. 78d • J. Galk, K. Leschonski; K. Legenhausen, Technische Universität Clausthal, 38678 Clausthal-Zellerfeld, GERMANY**

**A Theoretical Analysis of Horizontal High Density Pneumatic Transport of Powders • 2:45 PM • Paper No. 78e • J. Hong; Y. Tomita, Kyushu Institute of Technology, Kitakyushu 804, JAPAN**

*Break—3:00 PM*

**Gas-particle Flow in Vertical Tubes • 3:15 PM • Paper No. 78f • S. Dasgupta, R. Jackson, S. Sundaresan; Princeton University, Princeton, NJ**

**Pulse Jet Cleaning of Rigid Filter Elements at High Temperatures • 3:30 PM • Paper No. 78g • F. Löffler, S. Babner; Univ. Karlsruhe (TH), D-76128 Karlsruhe, GERMANY**

**Pick-Up and Saltation Relationships and Inter-Relationships in Pneumatic Conveying • 3:45 PM • Paper No. 78h • G.E. Klinzing; F. Cabrejos, University of Pittsburgh, Pittsburgh, PA**

*Summary:*

**Summary Paper: Solids Transport, Separation & Classification • 4:00 PM • Paper No. 78i • Prof. B. Pfeffer, New Jersey Institute of Technology, Newark, NJ, and Prof. S. Savage, McGill University, Montreal, Quebec, CANADA**

*Discussion & Concluding Remarks—4:30 PM*

**[79]**

**Wednesday, August 17  
5:30-7:00 PM  
Colorado Ballroom B**

**Posters for Particle Characterization**

**Sponsored by the Particle Technology Forum**

**Catalysis of Ni Particles Dispersed in Anodic Oxide Films Over Aluminum Wire • 5:30 PM • Paper No. 79a • A. Ueno; N. Ohji, T. Mizushima, N. Kakuta, Shizuoka University, Shizuoka 432, JAPAN**

**The Role of the Particle Characterization Laboratory in Industry • 5:30 PM • Paper No. 79b • M.A. Khalili; DuPont Central Science and Engineering (CS&E), Newark, DE**

**Effect of Thermal Diffusion on Gravitational Particle Size Analysis • 5:30 PM • Paper No. 79c • T. Allen; R.D. Nelson, DuPont Central Science and Engineering (CS&E), Wilmington, DE**

**Johnson's SB vs. the Log-normal Distribution for the Mathematical Representation of Particle Size Distributions • 5:30 PM • Paper No. 79d • A.B. Yu; The University of New South Wales, Kensington, NSW, 2033, AUSTRALIA**

**Annealing Effects of Small Particle-YBCO on Properties of the Superconductor • 5:30 PM • Paper No. 79e • H. Kezuka,\* N. Hosokawa, K. Hirata, K. Ishibashi, Tokyo Engineering University, Hachioji, Tokyo 192, JAPAN**

**On the Possibility of Using Elements of Information Theory for Particle Layer Description • 5:30 PM • Paper No. 79f • A. Yelshin,\* Polytechnic Institute, Novopolotsk, BELARUS (USSR)**

**Particulate Solids Characterization by Optical Multispectral Analysis • 5:30 PM • Paper No. 79g • G. Bonifazi,\* Universita Degli Studi di Roma—La Sapienza, Via Eudossiana, Rome 18 00184, ITALY**

**On-line Instrumentation for Particle Size Distribution Analysis of Industrial Colloidal Slurries Using Ultrasound • 5:30 PM • Paper No. 79h • H.P. Pendse,\* A. Sharma, University of Maine, Orono, ME**

**Ultrasound Characterization of Concentrated Colloidal Suspensions Containing Non-Spherical Particles • 5:30 PM • Paper No. 79j • H. Pendse, W. Han,\* Univ. of Maine, Orono, ME**

**Fiber Optic Dynamic Light Scattering from Concentrated Dispersion: Particle Sizing • 5:30 PM • Paper No. 79k • D. Fairhurst, W. Tschamuter, B. Weiner, Brookhaven Instruments Corp., Holtsville, NY, H. Dhadwal, K. Suh, SUNY at Stony Brook, New York**

**Standing Probe Microscopy Characterization of Micron Sized Particles • 5:30 PM • Paper No. 79k • A. Garcia, Arizona State University, Tempe, AZ**

**[80]**

Wednesday, August 17  
5:30-7:00 PM  
Colorado Ballroom B

### Posters for Agglomeration & Size Enlargement

Sponsored by the Particle Technology Forum

**The Effect of Humidity on the Diametral Compressive Strength of Tablets and on the Compaction Process • 5:30 PM • Paper No. 80a • J. Zimmer,\* K. Sommer, Tech. Univ. of Munich, Freising-Weihenstephan, GERMANY**

**Ferrite Additions Substitute for Bentonite in Pelletizing Process • 5:30 PM • Paper No. 80b • V.P. Khaidukov,\* S.L. Zevin, M.V. Tuchina, V.A. Dudina, Polytechnical College, Lipetsk, RUSSIA**

**Fundamental Studies of Fluidized Drum Granulation • 5:30 PM • Paper No. 80c • J. Litster,\* R. Sarwono, University of Queensland, QLD 4072, AUSTRALIA**

**On the Mechanics of Granulation • 5:30 PM • Paper No. 80d • B. Ennis,\* A. Adetayo, DuPont Company, Wilmington, DE**

**A Stability Analysis of Granulation Involving Multiple Growth Mechanisms • 5:30 PM • Paper No. 80e • A. Adetayo,\* B. Ennis, DuPont Company, Wilmington, DE**

**Boric Acid as Compacting and Glazing Agent • 5:30 PM • Paper No. 80f • L.I. Hayati,\* C.W. Campbell, Borax Research, Chessington, Surrey, KT9 1SJ, UK**

**Determination of Compressibility, Side Pressure and External Friction of Metal Powders • 5:30 PM • Paper No. 80g • S. Mironets,\* Brooklyn, NY**

**Powder Agglomeration in a Lodige Granulator • 5:30 PM • Paper No. 80h • F. Hoornaert,\* S. Pratsinis, Univ. of Cincinnati, OH, B. Scarlett, Delft Univ. of Technology, Delft, THE NETHERLANDS**

**[81]**

Wednesday, August 17  
5:30-7:00 PM  
Colorado Ballroom B

### Posters for Crystallization & Precipitation

Sponsored by the Particle Technology Forum

**The Influence of Magnetic Fields on the Crystallisation of Materials • 5:30 PM • Paper No. 81a • J.N. Sherwood,\* R.I. Ristic, A.M. Zikic (U. of Paisley), University of Strathclyde, Glasgow G1 1XL, Scotland, UK**

**Characterization of Hydrogen Pressure-Stripped Copper Products • 5:30 PM • Paper No. 81b • M.R. Peterson,\* U.S. Bureau of Mines, Salt Lake City, UT**

**Influence of the Crystallization Medium on Liquid Inclusions in Adipic Acid Crystals • 5:30 PM • Paper No. 81c • D.W. Grant,\* D. Law, Y. El-Said, University of Minnesota, Minneapolis, MN**

**Aggregation During Precipitation: Interpretation of Particle-size distributions • 5:30 PM • Paper No. 81d • M.J. Hounslow,\* University of Cambridge, Cambridge CB2 3RA, UK**

**[82]**

Wednesday, August 17  
5:30-7:00 PM  
Colorado Ballroom B

### Posters for Fluidization & Transport Phenomena

Sponsored by the Particle Technology Forum

**A Nondimensional Analysis for a Segregating Gas Fluidized Bed • 5:30 PM • Paper No. 82a • B. Kozanoglu,\* Universidad de las Americas-Puebla, Puebla, MEXICO**

**Theory of Binary Fluidization • 5:30 PM • Paper No. 82b • Y.A. Buyevich,\* S.K. Kapbasov, Urals State University, 620083, Ekaterinburg, RUSSIA**

**Microencapsulated Phase-Change Materials as Heat Transfer Media in Fluidized Beds • Paper No. 82c • J.D. Raspberry,\* R.C. Brown, Iowa State University, Ames, IA**

**Gas-Solids Fluidization at Less Than Atmospheric Pressure • 5:30 PM • Paper No. 82d • J.V. Fletcher,\* The Univ. of Utah, Salt Lake City, UT**

**The Minimum Fluidization, Attrition and Elutriation of Limestone Particles • 5:30 PM • Paper No. 82e • S.-M. Shih,\* W.-T. Tsai, L.-P. Leu, National Taiwan University, Taipei, TAIWAN, ROC**

**Bed Expansion and Average Bubble Rise Velocity in a Gas-Solid Fluidized Bed • 5:30 PM • Paper No. 82f • A.A. Al-Zahrani,\* M.A. Daous, King Abdulaziz University, Jeddah, 21413, SAUDI ARABIA**

**Temperature Distribution within a Discontinuous Rotative Grain Dryer • 5:30 PM • Paper No. 82g • K.J. Park,\* L.F.T. Alonso, O.A. Espinola, L.F.G. Godol, A.W. Mazzonetto, F.K. Natsumeda, H.W. Oliveira, DPPPA/FEAGRI/UNICAMP, 13081-970 Caixa Postal 6011, Campinas—S.P., BRAZIL**

**Some Solutions to the Problems of Moisture Uptake by Packed Columns of Detergent Powders • 5:30 PM • Paper No. 82h • B. Ahtchi-Ali,\* I.V. Nicolaescu, G. Tardos, Unilever Research U.S., Inc., Edgewater, NJ**

**A Numerical Simulation of Spouted Beds Based on a Two-Fluid Model • 5:30 PM • Paper No. 82i • K. Nagata, M. Nakamura,\* K. Mulase, S. Toyama, Nagoya University, Chikusa-ku, Nagoya, 464-01, JAPAN**

**Particle Velocities in Gas-Fluidized Beds • 5:30 PM • Paper No. 82j • J.P.K. Seville,\* S.J.R. Simons, C.J. Broadbent (U. of Birmingham), D.J. Parker & T.D. Beynon (U. of Birmingham, University of Surrey, Guildford, Surrey GU2 5XH, UK**

**Spheroidal CaCO<sub>3</sub> Production from Concentrated Solutions in a Pellet Reactor • 5:30 PM • Paper No. 82k • G. VanWeert,\* M. Schöller & L.F.J. Sijstermans, Delft University of Technology, 2628 RX Delft, THE NETHERLANDS**

**Local Measurements of Gas and Fluid Phase Parameters in a Three Phase Agitated Reactor • 5:30 PM • Paper No. 82l • R. Guder,\* N. Räßiger, Universität Bremen, 28334 Bremen, GERMANY**

**Segregation Potential in Fluidized Beds of Mixed Particles • 5:30 PM • Paper No. 82m • M.G. Rasul,\* V. Rudolph, S.C. Saxena (University of Illinois), University of Queensland, Brisbane, QLD 4072, AUSTRALIA**

**Electrical Capacitance Tomography for Flow Imaging in Fluidized Beds • 5:30 PM • Paper No. 82n • F.T. Kühn, J. Marijnissen, R. Mudde, J. Schouter, H. van den Akker, C. van den Bleek, B. Scarlett, Delft Univ. of Technology, Delft, THE NETHERLANDS**

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Wednesday, August 17  
5:30-7:00 PM  
Colorado Ballroom B

### Posters for Particle Interactions, Tribology & Assemblies

Sponsored by the Particle Technology Forum

**Measuring Adhesive Forces Between Solids • 5:30 PM • Paper No. 83a • M. Tirrell,\* V.S. Mangipudi, A.V. Pocius (3M), University of Minnesota, Minneapolis, MN**

**Particle Charging at High Temperature by Boxer Charger • 5:30 PM • Paper No. 83b • J. Ida,\* T. Matsuyama, H. Yamamoto, Soka University, Hachioji, Tokyo 192, JAPAN**

**Isotropic Compression of Mixtures of Hard and Soft Spheres • 5:30 PM • Paper No. 83c • C. Thornton, L.M. Toland,\* Aston University, Birmingham B4 7ET, UK**

**Surface Characterization of Particulate Materials using Inverse Gas Phase Chromatography • 5:30 PM • Paper No. 83d • D.R. Williams,\* Imperial College of Science, Technology and Medicine, London, SW7 2BY, UK**

**Assessment of Powder Reaction Rate from the Number of Contact Points Between Particles • 5:30 PM • Paper No. 83e • A. Shimizu,\* Y.J. Hao (U. of Newcastle), M. Inagaki, Hokkaido University, 060, Sapporo 060, JAPAN**

**Compressive Mechanics of Small Particles: Theory and Experiment • 5:30 PM • Paper No. 83f • B. Briscoe,\* K.K. Liu, D.R. Williams, Imperial College of Science, Technology and Medicine, London SW7 2BY, ENGLAND**

**Contact Adhesion of Carbon Fibres • 5:30 PM • Paper No. 83g • D. Williams,\* B. Briscoe, J. Law, Imperial College of Science, Technology and Medicine, London SW7 2BY, ENGLAND**

**Surface Energy Calculations of Natural Hydrophobic Minerals by the Lifshitz Theory and its Correlation with Gamma-C • 5:30 PM • Paper No. 83h • Ö. Özcan,\* A. Bulutcu, O. Receptoglu, Istanbul Technical University, Maslak 80626, Istanbul, TURKEY**

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Wednesday, August 17  
5:30-7:00 PM  
Colorado Ballroom B

**Posters for Comminution & Attrition**

Sponsored by the Particle Technology Forum

Fracture Characteristics of Superabrasive Diamond and cBN Micron Powders • 5:30 PM • Paper No. 84a • T.F. Dumm, General Electric Company, Worthington, OH

Diametrical Compression Tests: Computer Simulated Experiments • 5:30 PM • Paper No. 84b • C. Thornton, K.K. Yin, M.T. Ciomocos, M.J. Adams (Unilever), Aston University, Birmingham B4 7ET, UK

Milling of Ceramic Powders in a Centrifugal Barrel Mass Finisher • 5:30 PM • Paper No. 84c • K.J. Nilsen, Dow Chemical Company, Midland, MI

Inorganic Fine Powders for Technical Ceramics: Paradigms for Process Development • 5:30 PM • Paper No. 84d • K.S. Venkataraman, Alcoa Technical Center, Alcoa Center, PA

Recent Developments of Fine Grinding in China • 5:30 PM • Paper No. 84e • G. Gai, Y. Jin, S. Lu (U. of Sci. & Tech.), Tsinghua University, Beijing 100084, CHINA

Method of Optimal Design of the Fine Jet Grinding Mills • 5:30 PM • Paper No. 84g • I.N. Dorokhov, D.I. Eskin, T.H. Phuc, Mendeleev Russian University of Chemical Technology, Moscow, 125190, RUSSIA

A New Vibratory Grinding Mill that is Versatile and Energy Efficient • 5:30 PM • Paper No. 84h • B.H. Winn, Microgrinding Systems, Inc., Little Rock, AR

Pulverization of the Thermoplastic Materials Using Solid State Shear Extrusion • 2:15 PM • Paper No. 84i • A. Riahi, G. Ivanov, T. Shutov, H. Arastoopour, Illinois Institute of Technology, Chicago, IL

Analysis of Fluidized Bed Jet Grinding and Attrition Using Cubic Spline Interpolation • 5:30 PM • Paper No. 84j • H.B. Eldredge, S.D. Lewis (Westinghouse), University of Idaho, Idaho Falls, ID

Pulse Pneumo-Grinding Method and Devices • 5:30 PM • Paper No. 84k • V.N. Pachin, Structural Macrokinetics Institute, Tomsk Branch, RUSSIA

Improved Comminution through Short-Pulse Microwave Treatment • 5:30 PM • Paper No. 84l • J.B. Salsman, R.L. Williamson, W.K. Tolley, D.A. Rice, United States Department of Labor, Salt Lake City, UT

The Effect of Size Distribution of Kaolin Ores of Different Mineralogical Compositions on the Production of Clayey Size • 5:30 PM • Paper No. 84m • N.A. Abdel-Khalek, M.A. Arafat, Central Metallurgical R&D Institute, Cairo, EGYPT

The Minimum Fluidization, Attrition and Elutriation of Limestone Particles • 3:30 PM • Paper No. 84n • S.-M. Shih, W.T. Tsai, National Taiwan University, Taipei, TAIWAN ROC

Effect of Particle Size on Attrition • 5:30 PM • Paper No. 84o • M. Ghadiri, Z. Zhang, University of Surrey, Guildford, Surrey GU2 5XH, UK

On the Quantum Comminution Limit of Crystals • 5:30 PM • Paper No. 84p • V.A. Kuznetsov, A.G. Lipson, Russian Academy of Sciences, Moscow, Russia

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Thursday, August 18  
5:30-7:00 PM  
Colorado Ballroom B

**Posters for Particle Formation in Gases**

Sponsored by the Particle Technology Forum

Design of an Annular Denuder for Industrial Production Processes of Nano-Sized Particles—A Calculation Procedure • 5:30 PM • Paper No. 85a • M. Koyro, H. Sauter, Kernforschungszentrum Karlsruhe GmbH, D-76021 Karlsruhe, GERMANY

Bipolar Equilibrium Charge Distributions for Large Aggregates • 5:30 PM • Paper No. 85b • J.-C. Lin, S.-H. Cheng, R.V. Calabrese, A. Ranade (Particle Tech. Inc.), J.W. Gentry, University of Maryland, College Park, MD

Coagulation and Sintering of Fractal Aggregates: A Deterministic Approach • 5:30 PM • Paper No. 85c • S.E. Pratsinis, S. Vemury, K.A. Kusters, University of Cincinnati, Cincinnati, OH

Formation of Al<sub>2</sub>O<sub>3</sub> and TiB<sub>2</sub> Powder Mixtures by High Temperature Synthesis • 5:30 PM • Paper No. 85d • D.W. Readey, P. Tefft, J.J. Moore, The Colorado School of Mines, Golden, CO

Reactive Atmosphere Synthesis of SiC Powders • 5:30 PM • Paper No. 85e • R.L. Miller, D.W. Readey, J.J. Moore, The Colorado School of Mines, Golden, CO

Submicron TiB<sub>2</sub> Powders by Vapor Transport Assisted Reactions • 5:30 PM • Paper No. 85f • C. Rando, D.W. Readey, J.J. Moore, The Colorado School of Mines, Golden, CO

Sensitivity of Total Mass Deposition Rate and Resulting Deposit Microstructure to Morphology of Coagulation-Aged Aerosol Populations of Aggregated Primary Particles • 5:30 PM • Paper No. 85g • D.E. Rosner, M. Tassopoulos, P. Tandon, Yale University, New Haven, CT

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Thursday, August 18  
5:30-7:00 PM  
Colorado Ballroom B

**Posters for Multiphase Flow**

Sponsored by the Particle Technology Forum

Separation of Drops and Solid Particles in a 3 Phase Flow • 5:30 PM • Paper No. 86a • K. Leschonski, B. Benker, Technische Universität Clausthal, D-3392 Clausthal-Zellerfeld, GERMANY

Numerical Analysis of Experimental NMR Slurry Velocities and Concentrations • 5:30 PM • Paper No. 86b • R. Lyczkowski, J.X. Bouillard, J. Ding, Argonne National Laboratory, Argonne, IL

Predicting Practical Dust Explosion Risk and Achieving Optimal Explosion Protection Through Explosion Venting • 5:30 PM • Paper No. 86c • S.M. Lemkowitz, P.G.J. van der Wel (TNO), B. Scarlett, Delft University of Technology, 2600 GA Delft, THE NETHERLANDS

Influence of Elastic Deformation and Surface Roughness on the Detachment of Colloidal Particles from Surfaces • 5:30 PM • Paper No. 86d • S. Das, M.M. Sharma, The University of Texas at Austin, Austin, TX

Particle Dispersion in Wake-Generated Turbulence • 5:30 PM • Paper No. 86e • C.T. Crowe, T. Troutt, S. Wang, Y. Yang, Washington State University, Pullman, WA

A New Dry Powder Dispersion System for Particle Size Analysis Using Aerodynamic Time-of-Flight Technique • 5:30 PM • Paper No. 86f • T.A. Poole, Amherst Process Instruments, Inc. Hadley, MA

Non-Intrusive Measurements of Particle-Wall Collision Properties • 5:30 PM • Paper No. 86g • J. Sinclair, H. Maseh, M. Shahnam, F. Shaffer, Carnegie Mellon University, Pittsburgh, PA

Stability of Bounded Shear-flow of Granular Materials • 5:30 PM • Paper No. 86h • S. Sundaresan, R. Jackson, Princeton University, Princeton, NJ

Construction and Use of a Strengthened 20-Litre Cell for Dust Explosion Testing at Super-Ambient Conditions • 5:30 PM • Paper No. 86i • S. Leschonski, L. Sluijs, S.M. Lemkowitz, P.G.J. Van der Wel, B. Scarlett, Delft Univ. of Technology, 2628 BL Delft, THE NETHERLANDS

Interactions of Moving Bubbles in Non-Newtonian Fluids • 5:30 PM • Paper No. 86j • J. Starke, N. Rübiger, Universität Bremen, 28334 Bremen, GERMANY

Flow & Transport in Porous Media • 5:30 PM • Paper No. 86k • M. Rashidi, Lawrence Livermore National Laboratory, Livermore, CA

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Thursday, August 18  
5:30-7:00 PM  
Colorado Ballroom B

**Posters for Powder Mechanics & Material Storage**

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Thursday, August 18  
5:30-7:00 PM  
Colorado Ballroom B

**Posters for Particle Modification & New Processes**

Sponsored by the Particle Technology Forum

Products of Mechanochemistry in the Powder Technology of the Producing of Composites Based on Polymers • 5:30 PM • Paper No. 88a • S.I. Nechaeva, Y.P. Toporov, Russian Academy of Science, 117915 Moscow, RUSSIA

The Effect of Gaseous Media Mechanical Alloying on the Process of Reactor Diffusion in Metal-Non Metal Systems • 5:30 PM • Paper No. 88b • A.A. Popovich, V.P. Reva, V.N. Vasilenko, Far Eastern State Technic University, Vladivostok 690600, RUSSIA

Mechanochemical Technology of Synthesis of Refractory Compounds in MeO (+ Mg(Al) + Me (Nonmetal) Systems) • 5:30 PM • Paper No. 88c • A.A. Popovich, V.P. Reva, V.N. Vasilenko, Far Eastern State Technic University, Vladivostok 690600, RUSSIA

Microstructure and Properties of Titanium Carbide and Titanium Carbide Based Alloys Obtained by Mechanochemical Synthesis • 5:30 PM • Paper No. 88d • A.A. Popovich, Far Eastern State Technic University, Vladivostok 690600, RUSSIA

Mechanochemical Technology of the Fine Comminution and Simultaneous Modification of Inorganic Materials Surface • 5:30 PM • Paper No. 88e • V.A. Kuznetsov, T.S. Ivanova, B.V. Derjaguin, Russian Academy of Sciences, Moscow, RUSSIA

Freshly Formed Surface of LiF Disperse Particles as the Mott's Insulator • 5:30 PM • Paper No. 88f • A.G. Lipson, V.A. Kuznetsov, B.V. Derjaguin, Russian Academy of Sciences, Moscow, RUSSIA

Mechanochemical Synthesis of Polymeric  $\pi$ -Complexes on the Freshly Formed Surface of Lithium Fluoride Disperse Particles and their Electrophysical Properties • 5:30 PM • Paper No. 88g • V.A. Kuznetsov, A.G. Lipson, T.S. Ivanova, Russian Academy of Sciences, Moscow, RUSSIA

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Thursday, August 18  
5:30-7:00 PM  
Colorado Ballroom B

### Posters for Dispersion, Rheology & Mixing

Sponsored by the Particle Technology Forum

Filter Cake Formation in Cross-Flow Filtration of Colloidal Suspensions • 5:30 PM • Paper No. 89a • D. Jiao\*, M. Sharma, The University of Texas at Austin, Austin, TX

A Stokesian Dynamics Model for the Flow and Capture of Colloidal Particles in Porous Media • 5:30 PM • Paper No. 89b • S. Vitthal\*, M. Sharma, The University of Texas at Austin, Austin, TX

The Influence of Mixing on the Solid-State Reaction in BaTiO<sub>3</sub> Synthesis • 5:30 PM • Paper No. 89c • D. Ray\*, C. Huang, National Cheng-Kung University, Tainan, Taiwan 70101, ROC

The Influence of Particle Size on the Stability of Suspensions • 5:30 PM • Paper No. 89d • E. Gabrys-Deutscher\*, K. Leschonski, Technische Universität Clausthal, 38678 Clausthal-Zellerfeld, GERMANY

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Thursday, August 18  
5:30-7:00 PM  
Colorado Ballroom B

### Posters for Solids Transport, Separation & Classification

Sponsored by the Particle Technology Forum

Simulation of a New Crossflow Moving Bed Heat Exchanger-Filter (MHEF): Effect of the Pressure Drop • 5:30 PM • Paper No. 90a • A. Macias-Machin\*, G. Winter, V. Henriquez, S. Garcia, E.T.S.I.I. de Las Palmas, 35017 Las Palmas de Gran Canaria, SPAIN

The Effect of Particle Size Distribution on the Behaviour of Settling Slurries in Horizontal Pipes • 5:30 PM • Paper No. 90c • R. Clift\*, G. Addie, K. Wilson, University of Surrey, Guildford, Surrey GU2 5XH, UK

Pressure Drop through Annular Static Mixer Dryer • 5:30 PM • Paper No. 90d • K.J. Park, L.F.T. Alonso, W.A. Correa, O.A. Espinola\*, L.F.G. Godoi, A.W. Mazzonetto, FEAGRI/UNICAMP, 13081-970 Caixa Postal 6011, Campinas—S.P., BRAZIL

Precise Determination of Filter Cake Thickness by a Filter Chamber with an Expanded Area • 5:30 PM • Paper No. 90e • W.F. Leu\*, M.-H. Lee, National Taiwan University, Taipei 106, TAIWAN, ROC

A Scale-Up Separation Model for Hydrocyclones in Consideration of the Non-Newtonian Behavior of Suspensions • 5:30 PM • Paper No. 90f • E. Ortega-Rivas\*, L. Svarovsky, University of Chihuahua, Chihuahua, MEXICO

Filter Media Selection for Nutsche Filter-Dryers for Pharmaceutical Intermediates and Final Sterile Products • 5:30 PM • Paper No. 90g • B.A. Perlmutter\*, Rosemund, Inc., Charlotte, NC

Particle Classification by Vibration • 5:30 PM • Paper No. 90h • H. Khoory\*, H. Mahgerefteh, University College London, London WC1E 7JE, ENGLAND

Granular Dynamics Modeling of Vibration-Induced Convection of Rough Inelastic Spheres • 5:30 PM • Paper No. 90i • A.D. Rosato\*, Y. Lan, New Jersey Institute of Technology, Newark, NJ

Two Phase (Gas-Solid) Particle Flow in Vertical Mixer Tubes Equipped with Motionless Mixer Elements • 5:30 PM • Paper No. 90j • J. Gyenis\*, L. Németh, Research Institute of Chemical Engineering of the Hungarian Academy of Sciences, HUNGARY

Gas-Solid Flow in Inclined Pipeline • 5:30 PM • Paper No. 90k • P. Marjanovic\*, D.J. Mason, Centre for I Bulk Solids Handling, Glasgow G4 0BA, UK

The Effect of Pipeline Flow Conditioning on Low Velocity Gas-Solid Flow • 5:30 PM • Paper No. 90l • S. Barton\*, M.G. Jones, D. Mills, Centre for I Bulk Solids Handling, Glasgow G4 0BA, UK

New Two Stage Separation Process of Unburned Carbon from Coal Fired Flyash • 5:30 PM • Paper No. 90m • S. Mori\*, T. Sawa, H. Miyagawa, N. Ohshita, Nagoya University, JAPAN

Solid-Flow Through Non-Mechanical L-Valves • 5:30 PM • Paper No. 90n • M.A. Daous\*, A.A. Al-Zahrani, King Abdulaziz University, Jeddah 21413, SAUDI ARABIA

Continuous Magnetic Separation of Fine Materials with a High Intensity Spiral Separator • 5:30 PM • Paper No. 90o • K. Schönert\*, M. Botsch, Technische Universität Clausthal, 38678 Clausthal-Zellerfeld, GERMANY

• 5:30 PM • Paper No. 90p • M.M. Rao\*, Indian Institute of Technology, Madras—600 036, INDIA

Structural Optimization of a Discontinuous Rotative Grain Dryer • 5:30 PM • Paper No. 90q • K.J. Park, R.F. Abraheó\*, L.F.T. Alonso, O.A. Braunbeck, O.A. Espinola, L.F.G. Godoi, A.W. Mazzonetto, F.K. Natsumeda, H.W. Oliveira, FEAGRI/UNICAMP, 13081-970 Caixa Postal 6011, Campinas—S.P., BRAZIL

Dry Separation of Fine Particle from Gases in Multilayer Packings • 5:30 PM • Paper No. 90r • J. Fischer, K. Leschonski, T.U. Clausthal, Clausthal-Zellerfeld, GERMANY

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DuPont Central Research  
and Development  
Experimental Station  
P. O. Box 80304  
Wilmington, DE 19880-0304



DuPont Central Research and Development

APPENDIX R

September 15, 1994

Professor Klaus Timmerhaus  
Department of Chemical Engineering  
University of Colorado at Boulder  
Engineering Center ECCH 1-43  
Campus Box 424  
Boulder, Colorado 80309-0424

Fax: 303-492-4241

Dear Klaus:

Your suggestion for the four future technologies for Material and Chemical Processing in your letter of August 31st is acceptable to me. I am progressing under the assumption that we have two tracts for Advanced Particle Technology.

I received Prof. Chris Macosko's fax suggesting two additional tracts for ceramics processing. I have no problem with this, except that it would be good to know if these tracts are indeed included because they will influence the papers we accept. Note that in Attachment 2 I have excluded advanced materials and ceramics from my list, assuming that these topics will be discussed in other tracts.

So for the present we are going with the design of Attachment 1 which selects eight topics each with an invited paper and a minimum of 15-minute papers/posters. Each session will be two hours of presentation followed by 1-1/2 hours of poster viewing. The Thursday mornings will be entirely devoted to workshop-type discussions and the summary. This gives us 132 presentations.

The topic titles will be left open for the present until I can sound out my committee. Attachment 2 currently suggests we ask for papers on topics included under the four headings. We might change these to "technology-based topics", depending on the response.

For the present, i.e., until our PTF elections are complete in November 1994, the organizing committee will consist of Prof. R. Pfeffer, Dr. M. Roco, Prof. L.-S. Fan, and myself (the Denver PTF organizing committee).

Regarding your other comments about plenary speakers, we all need to have a "world" view about our suggestions thinking of experts from other countries. I have no names in mind for the major plenaries, but am thinking about it. I will call you in a few days.

Sincerely yours,

SCIENCE & ENGINEERING LABORATORIES  
Particle Science & Technology (PARSAT)

A handwritten signature in dark ink, appearing to read "RD Davies", written in a cursive style.

Dr. Reg Davies  
Principal Division Consultant & Research Manager

RD/jef  
DAVIES13



## ATTACHMENT 2

We will accept abstracts in the following areas:

### Energy, Safety, Environmental

- Aerosol Technology
- Circulating Fluid Beds
- Combustion
- Comminution
- Dust Explosions
- Dust Handling & Cleaning
- Electrostatics
- Emission Control
- Gas/Solid Separation
- Liquid/Solid Separation
- Remediation

### Agriculture, Food, Pharmaceutical

- Coating
- Crystallization
- Dispersion Technology
- Drug Delivery
- Fluidized Bed Technology
- Food Technology
- Granulation
- Measurement & Control
- Pelletizing
- Rheology
- Solids Processing
- Spray Technology
- Tableting
- Time Release

### Solids Processing & Manufacturing

- Classification
- Drying
- Feeding & Metering
- Material Handling
- Measurement & Control
- Milling
- Mixing
- Packaging
- Pneumatic Conveying
- Process Scale Up
- Size & Morphology Control
- Storage

### Advanced Fundamentals

- Adhesion
- Attrition
- Coalescence
- Compaction
- Extrusion
- Flocculation
- Interparticle Forces
- Measurement & Control
- Mechanochemistry
- Modeling of Particle Processes
- Multiphase Flow Fracture Mechanics
- Nucleation
- Particle Coating
- Powder Mechanics
- Tribology