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Final Report

Development and Utilization of New Diagnostics for Dense-Phase Pneumatic Transport

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Summary

Dense-phase pneumatic transport is an attractive means of conveying solids. Unfortunately, because of the high solid concentrations, this transport method is a difficult regime in which to carry out detailed measurements. Hence most details of the flow are unknown.

In this context, the objectives of this research were to develop probes for local measurements of solid velocity and holdup in dense gas-solid flows, to test these probes in a setup transporting dense, cohesive solid plugs, to analyze the corresponding data, and to seek interaction with industry at all stages of this work. The importance of this research resides in the great number of processes involving dense gas-solid suspensions that may benefit from its results.

At the completion of this work, the results have exceeded the expectations outlined in the original proposal. The present report summarizes these accomplishments, which have led to six archival publications, two reviewed conference papers, ten formal presentations, various reports, and the award of five graduate degrees.

1. Introduction

In 1988, we proposed a program to develop new diagnostics for dense gas-solid suspensions, with particular interest toward the dense pneumatic transport of cohesive solid plugs. This program included three main objectives, as follows: to develop probes for local measurements of (1) local particle volume fraction and (2) individual particle velocities in dense gas-solid flows; and (3) to construct a bench-scale setup for transporting dense, cohesive solid plugs and to analyze data from the resulting tests.

The results of this program have exceeded our original expectations in all aspect of this research. These activities has led to publications in major research journals, as well as significant progress of interest to industry, primarily in the development of new measurement techniques.

In this final report, rather than reproducing earlier quarterly reports, journal publications, or yearly summaries of activities, we have chosen to provide a list of all papers, reports and presentations resulting from this project and acknowledging DOE sponsorship. Through these, the reader will find a thorough description of the research and its results. Before providing a list of these papers with their abstracts, we begin with a summary of our accomplishments.

2. Summary of accomplishments

The main objective of this work was to develop new instruments for dense gas-solid flows. Thus we have designed capacitance probes to measure local, time-dependent particle concentrations, and a new optical fiber probe based on laser-induced-phosphorescence to measure the velocity of individual particles.

2.1. Capacitance probes

We have described the principle of the capacitance diagnostic in [*Particulate Science & Tech.*, **7** 51:59 (1989)] and its calibration in [*Powder Tech.* **62**, 85-94 (1990)]. Briefly, this technique is based on a guard circuit that virtually eliminates all cable and stray capacitances, and thus allows volume fraction measurements of unprecedented accuracy. Calibration is achieved by verifying established homogenization models for the effective dielectric constant.

We have tested several different probe geometries, including a version that can be traversed through a suspension and an arrangement that allows non-invasive measurements near the wall of a vessel. By virtue of its geometry, the non-invasive 'wall' probe can also be combined with a different sensor mounted behind its central ground surface, so another flow parameter may be recorded simultaneously. For example, we have inserted a small, temperature-controlled platinum coil near the face of a 'wall' probe to measure heat flux across the wall.

In another combination of sensors, we have used a 'wall' probe to test the accuracy of a widely used technique that infers local particle concentration from the light back-scattered by a suspension onto an optical fiber (Fig. 1). To interpret the corresponding experiments, we have simulated the performance of the optical sensor using a Monte-Carlo technique. Our tests and simulations have shown that this optical method can be very inaccurate if the particle diameter is greater that that of the core of the fiber. Following this analysis, we have proposed guidelines for optimizing the accuracy of this diagnostic technique [*Applied Optics* (1992), in press].

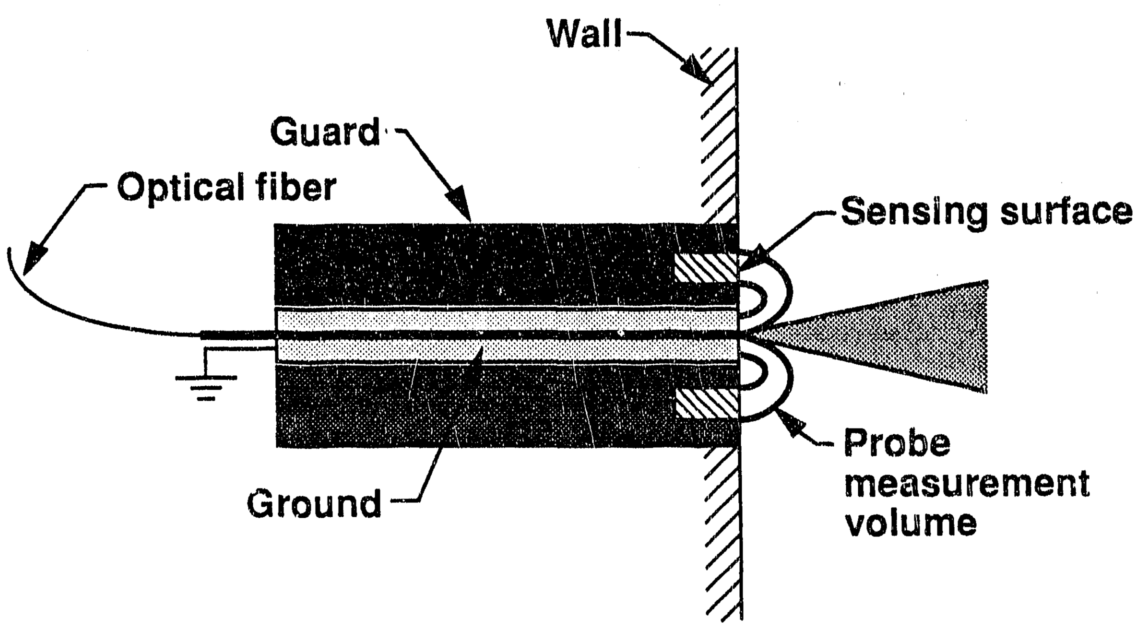

Fig. 1. The capacitance 'wall' probe combined with an optical fiber probe. Dimensions are not to scale. The semi-toroidal measurement volume shown is that of the capacitance probe. It penetrates approximately 2mm into the suspension.

In order to make the new capacitance technique available to other groups at a reasonable cost, we are now helping a small business commercialize our probes for low and high temperature applications.

2.2. Optical fiber anemometer

We have demonstrated the feasibility of the optical anemometer in [*Applied Optics* **30**, 1976-81 (1991)]. Figure 2 illustrates its principle of operation. Particles are coated with a phosphor of relatively long afterglow, which is excited by short pulses of light generated by the dye laser. This light is guided by an optical fiber to the probe centerline, where it is collimated by a graded-index rod lens. Depending on the size and volume fraction of the coated particles, only a few particles are illuminated. The phosphorescent coat makes a particle glow long enough to be detected as it passes in front of one of several peripheral fibers located at known distance away from the probe's centerline. The velocity of the particle is inferred from the time elapsed between its instantaneous excitation by the laser pulse and the detection of its peak afterglow by a photomultiplier tube (PMT) coupled to the detection fiber.

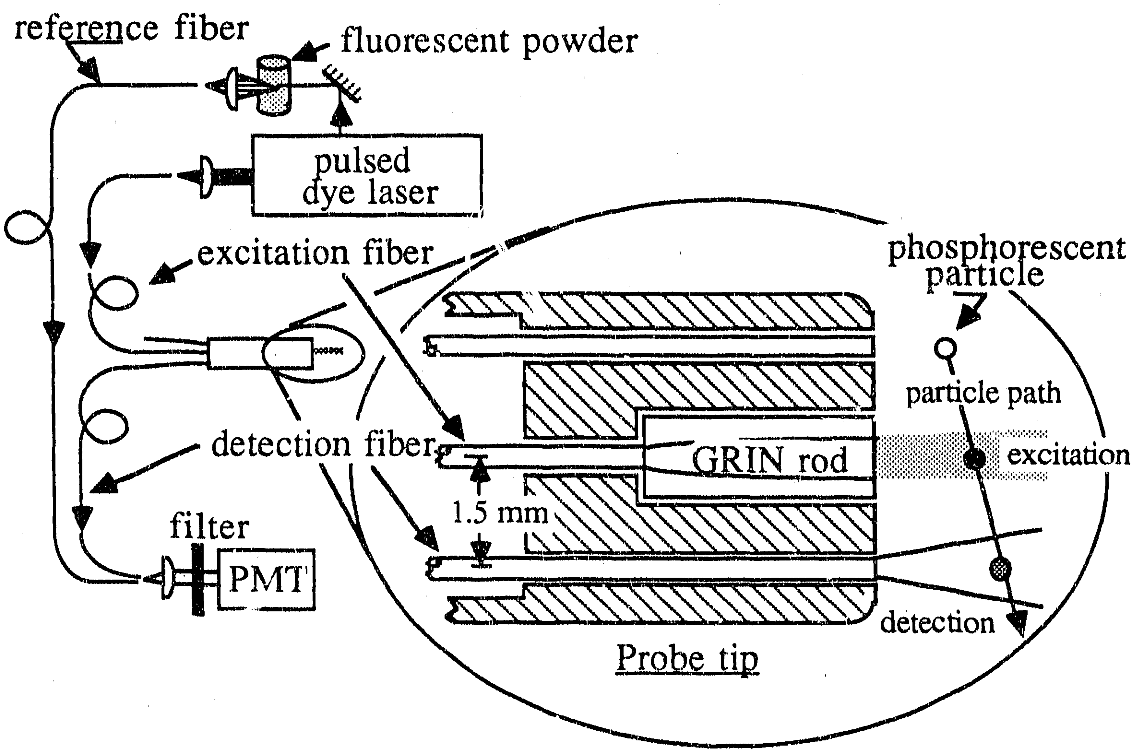

Fig. 2. Principle of operation of the probe. The cut through the probe tip shows the relative position of the GRIN lens and the excitation and detection fibers. Only one detection channel (filter, PMT) is shown.

To extract the particle time-of-flight, we have constructed behind the detector of each peripheral fiber a dedicated circuit that include analog electronics and a digital data acquisition system. The analog circuit detects the time of the peak afterglow in the presence of significant noise, and it is capable of distinguishing several consecutive peaks in the event of multiple particle passage. The digital unit includes a counter that measures the corresponding times of flight, and a microprocessor that transfers the resulting data to a computer through a parallel IEEE-488 interface.

2.3. Pneumatic transport of dense, cohesive plugs

Another objective of this work was to carry out experiments in a small pneumatic transport facility carrying dense plugs of fine, cohesive particles, and to interpret the resulting data. In the original proposal, we envisioned two mutually exclusive strategies for interpreting the experiments. These strategies may be called the 'collisional' and 'frictional' analyses.

For cohesionless materials, the observations of Konrad (1986) had indicated that plugs were behaving like fluids, in that their end faces had the shape of interfaces between immiscible liquids. Thus in the Project Work Plan, we suggested that collisional momentum exchange between grains might dominate the force transferred by static friction. In the event that it did, we proposed to analyze dense plug transport by extending previous theories for granular materials interacting through collisions, and by incorporating the influence of the gas flow that drives the motion of the grains. This approach is the 'collisional' analysis.

On the contrary, in the event that cohesive forces frustrated the relative motion of particles, we suggested that an analysis of dense, cohesive transport should simply focus on the rigid motion of a porous plug, driven by the flow of the interstitial gas and resisted by Coulomb friction at the walls. This is the 'frictional' analysis.

During the period necessary to construct and prepare the experiments, we carried out computer simulations in order to verify the rapid granular theories and boundary conditions that we would employ in the collisional analysis. Results of these simulations are presented in the next section.

However, once underway, the experiments revealed that the collisional analysis could not describe appropriately the flow of dense plugs.

Our first experiments produced dense plugs of relatively cohesionless hollow glass spheres (diameter 30 microns, density 0.3 g/cc). These plugs, however, were quite unstable. They would rise a short distance in the vertical 1" tube, then break and fall to the bottom of the tube. Then the particles collected near the distributor would be fluidized by the dry nitrogen used to convey them. Upon shutting the dry nitrogen, the particles would slowly sediment to form a loose packing at the bottom of the tube. In these experiments, there was no visual evidence that collisions were important while the glass spheres ascended the column as a coherent plug. Instead, we noticed that some particles adhered to the walls, creating an uneven film of grains there. Practitioners of dense pneumatic conveying call the creation of this film 'the seasoning of the pipe'. Typically, particles flow more smoothly once the tube has been 'seasoned'. The mechanism responsible for this improvement in the 'flowability' of plugs is unclear, although it is likely to resemble the use of fine graphite powder in lubrication.

New attempts to obtain dense, stable plugs with hollow glass spheres failed. We postulated that the earlier experiments involved glass spheres with a significant amount of adsorbed water that had made these unusually cohesive. Because we could not produce cohesive plugs with dry glass bubbles, we turned to flour, which is always cohesive thanks to asperities on the particle surface. In these experiments, we observed again a 'seasoned' layer of flour particies on the wall, and there was no visual evidence that collisions were involved in momentum transport at the wall.

Therefore, collisional interactions are probably not the mechanism responsible for momentum exchange at the wall in the transport of cohesive plugs. The situation is almost certainly different with horizontal plugs of large, weakly cohesive particles. There, collisions might play a role, as the plugs are not material entities, but rather resemble a wave constantly exchanging particles with the surroundings. Because our brief was to look into cohesive plugs, we did not run experiments into the cohesionless regime. Instead we focused on interpreting the experiments with flour plugs. The frictional analysis described in our 12-th quarterly report achieved this end satisfactorily.

We have also evaluated the performance of our newly developed diagnostic techniques in the presence of dense, cohesive plugs. There we have found that non-invasive probes like the capacitance 'wall' probe work well. In contrast, sensors with the slightest degree of intrusion cause the dense plugs to collapse. Nevertheless, we expect that dense, flowing suspensions will be less susceptible to intrusion from relatively small sensors such as the optical fiber anemometer.

2.4. Computer simulations of rapid granular flows

Because we had postulated that collisional interactions would be relevant to the dense pneumatic transport of particles, we began our studies by substantiating recent theories of rapid granular flows through computer simulations.

Thus we have verified the theory of Hanes, Jenkins & Richman (1988) for the rapid, steady shear flow of identical, smooth, nearly elastic disks driven by identical, parallel, bumpy boundaries. Results of this work appeared in [*Phys. Fluids A* **2** (6), 1042-44 (1990)]. Further, in examining the theory of Jenkins & Richman (1988) for the rapid flows of uniform smooth inelastic disks under simple shear, we have revealed the formation of microstructures there [*Phys. Fluids A* **3** (1), 47-57 (1991)].

Because granular flows depend strongly on the nature of their interaction with a boundary, we have also verified the boundary conditions calculated by Jenkins (1991) for spheres interacting with a flat, frictional surface [*Proc. ASCE Eng. Mech. Conf.*, Columbus, OH, May 1991]. Finally, we have studied the relaxation of smooth inelastic disks undergoing simple shear by comparing results of our simulations with the theoretical predictions of Jenkins and Richman (1988) [*Proc. 2nd US/Japan Conf. on Micromechanics of Granular Materials*, Potsdam, NY, July 1991].

3. <u>List of publications</u>

In this section we list all archival publications, conference proceedings, and presentations acknowledging the support of the DOE through this program. We also include abstracts of the archival publications and conference proceedings.

3.1. <u>Archival publications with abstracts</u>

- Acree Riley, C. & Louge, M.Y.: "*Quantitative Capacitive Measurements of Voidage in Dense Gas-Solid Flows*", Particulate Science & Tech., **7** 51:59 (1989).

New capacitance probes were developed for quantitative, time-dependent measurements of voidage in gas-solid flows. Based on a unique guard circuit which nearly eliminates all stray and cable capacitances, these probes are fast (2kHz) and they do not require *in situ* calibration. Two configurations were studied: small parallel plates for recording voidage profiles, and a non-intrusive design for local voidage measurements near a wall. Static tests were performed using a fixed bed of known voidage and dielectric constant. The probes were also demonstrated in a two-dimensional fluidized bed of glass beads.

- Louge M. & Opie M.: "*Measurements of the Effective Dielectric Permittivity of Suspensions*", Powder Tech. **62**, 85-94 (1990).

A technique to measure the effective dielectric permittivity of suspensions is described. In these measurements, test powders are suspended in petroleum jelly at any desired voidage. The technique is illustrated using spherical glass beads of various sizes, a catalyst powder with and without water contamination, metal spheres, and metal flakes. For each suspension, a model is selected to fit the data. In the context of metal flakes, a model is derived for the effective dielectric permittivity of a suspension of ellipsoids in an electric field of random orientation. For complex powders, the technique is shown to represent a necessary step towards quantitative measurements of voidage using capacitance diagnostics.

- Louge, M.Y., Iyer, S.A., Giannelis, E.P., Lischer, D.J. & Chang, H.: "*Optical Fiber Measurements of Particle Velocity using Laser-Induced-Phosphorescence*", Applied Optics **30**, 1976-81 (1991).

An optical fiber anemometer that uses laser-induced-phosphorescence to measure particle time-of-flight in dense gas-solid suspensions is described. The anemometer is tested using a spinning disc coated with a phosphor having a persistent afterglow. The diagnostic technique is illustrated by measuring the velocity of free-falling particles coated with the same phosphor. Monte-Carlo simulations are employed to determine the optical characteristics of the probe, including its measurement volume.

• Lischer, D.J. & Louge, M.Y.:*"Optical fiber measurements of particle concentration in dense suspensions: calibration and simulation"*, Applied Optics (1992), in press.

A fiber optic sensor that measures particle volume fraction in dense suspensions is calibrated against a quantitative capacitance probe. For homogeneous, dense, random suspensions of smooth, monodisperse, transparent dielectric spheres, the calibration is simulated using a ray-tracing Monte Carlo algorithm that predicts systematic uncertainties of the sensor's output, the extent of its measurement volume, and effects of changing its optical properties. The simulation shows that the output and accuracy of the sensor increase with decreasing sphere diameter and with increasing N.A. of the fiber. The output increases also when the ratio of the indices of refraction of the sphere and the suspending medium is increased. For small particles the measurement volume scales as the average interparticle distance.

• Louge M., Jenkins J.T. & Hopkins M.A.: "*Computer Simulations of Rapid Granular Shear Flows between Parallel Bumpy Boundaries*", Phys. Fluids A **2** (6), 1042-44 (1990).

This paper compares the results of numerical simulations for the rapid, steady shear flow of identical disks with the recent predictions of Hanes, et al. [J. Appl. Mech. **55**, 969 (1988)] for the shear stress, normal stress and gap width. The smooth and nearly elastic disks are driven by identical, parallel, bumpy boundaries. The variations of the dynamic friction coefficient are confirmed by the simulations. The coefficient may be made large or small by suitably preparing the boundaries of the cell. The simulations also indicate that the predictions of kinetic theory apply to gaps as small as three particle diameters in width.

• Hopkins, M.A. & Louge M.: "*Inelastic Microstructure in Rapid Granular Flows of Smooth Disks*", Phys. Fluids A **3**(1), 47-57 (1991).

Computer simulations of two-dimensional rapid granular flows of uniform smooth inelastic disks under simple shear reveal a dynamic microstructure characterized by the local, spatially anisotropic agglomeration of disks. A spectral analysis of the concentration field suggests that the formation of this inelastic microstructure is correlated with the magnitude of the total stresses in the flow. The simulations confirm the theoretical results of Jenkins and Richman [J. Fluid Mech. **192**, 313 (1988)] for the kinetic stresses in the dilute limit and for the collisional stresses in the dense limit, when the size of the periodic domain used in the simulations is a small multiple of the disk diameter. However the kinetic and, to a lesser extent, collisional stresses both increase significantly with the size of the periodic domain, thus departing from the predictions of the theory that assumes spatial homogeneity and isotropy.

3.2. Conference papers, reviewed

• Louge, M., Jenkins, J.T. & Hopkins, M.A., *"Computer simulations of rapid granular flows interacting with a flat, frictional boundary"*, Proc. ASCE Eng. Mech. Conf., Columbus, OH, May 1991.

This paper compares the results of numerical simulations for the rapid, steady flow of identical spheres colliding with a flat frictional boundary with the recent predictions of Jenkins [*J. Appl. Mech.*, in press (1991)] for the dynamic friction coefficient and flux of fluctuating energy at the boundary. The predicted variation of the dynamic friction coefficient is observed in the simulations. However, because the model ignores the spin fluctuations, it provides only a qualitative description of the flux.

• Louge, M., Jenkins, J.T. & Hopkins, M.A., *"The relaxation of the second moments in rapid shear flows of smooth disks"*, Proc. of the 2nd US/Japan Conference on Micromechanics of Granular Materials, Clarkson University, August 1991.

This paper compares the results of numerical simulations for two-dimensional, rapid, homogeneous shear flows of identical, smooth, inelastic disks with the predictions of Jenkins and Richman [*JFM* **192**, 313-328 (1988)] for the relaxation of the second moments of the velocity distribution function following a homogeneous, but anisotropic disturbance of their steady values. For nearly elastic disks, the time-history of the relaxation is in excellent agreement with the theory in both its dense and dilute limits. However, deviations are observed in the case of inelastic particles.

3.3. Presentations

- *"Development of Diagnostics Instruments at Cornell"*, invited presentation, Amoco Oil R&D, Naperville, IL, June 6, 1990.
- *"Development of Diagnostics for Pneumatic Transport"*, invited review, DOE Research Assessment, Bethesda, MD, May 23, 1990.
- *"Computer Simulations of Rapid Granular Flows"*, MAE Colloquium, Cornell University, February 27, 1990.
- *"Particulate Research at Cornell"*, invited lecture, JASON/MITRE Summer Study, San Diego, CA, June 26, 1989.
- *"Optical Fiber Measurements of Particle Velocity using Laser-Induced-Phosphorescence"*, 21st Annual Meeting of the Fine Particle Society, San Diego, CA, August 23, 1990.
- *"Inelastic Microstructure in Rapid Granular Flows of Smooth Disks"*, 21st Annual Meeting of the Fine Particle Society, San Diego, CA, August 22, 1990.
- *"Inelastic Microstructure in Rapid Granular Flows of Smooth Disks"*, Eighth Army Conference on Applied Mathematics and Computing, Cornell University, June 19 1990.
- *"Development of Diagnostics for Pneumatic Transport"*, NSF-DOE Workshop on Solids Transport, Pleasanton, CA, May 18, 1989.
- *"Development of Diagnostics for Pneumatic Transport"*, NSF-DOE Workshop on Solids Transport, Gaithersburg, MD, October 1, 1990.
- *"La Mécanique des Milieux Dispersés à Cornell"*, invited presentation, IUSTI, Université de Provence, Marseilles, France, November 15, 1991.

3.4. Reports

- Louge, M.: *"Development and Utilization of New Diagnostics for Dense-Phase Pneumatic Transport"*, twelve consecutive Quarterly Technical Progress Reports for the period October 1, 1988 to September 30, 1991, DOE Contract DE-AC22-88PC88947.
- Louge, M.: *"Development and Utilization of New Diagnostics for Dense-Phase Pneumatic Transport"*, DOE Research Assessment Report, DOE Contract DE-AC22-88PC88947, May 1990.
- Louge M. & Giannelis E.: *"Development of Diagnostics for Pneumatic Transport"*, Proceedings of the Joint DOE/NSF Workshop on Fluid-Solids Transport, S. Rogers, ed, Department of Energy, Pittsburgh Energy Technology Center (1989), pp. 40-52.
- Louge M., Jenkins J.T. & Giannelis E.: *"Development of Diagnostics for Pneumatic Transport"*, Proceedings of the Joint DOE/NSF Workshop on Fluid-Solids Transport, Gaithersburg, MD, October 1-3, 1990, DOE Contract DE-AC-22-88PC-88947.

4. Graduate students

Five graduate students were trained during the course of this project. They are: Catherine Acree Riley (M.S., 1989), Michael V. Opie (M.S., 1990), Subramanyam Iyer (M.S., January 1991), D. Jeffrey Lischer (Ph.D., 1991), and Hongder Chang (Ph.D., 1991). Catherine Acree Riley and Michael V. Opie developed the capacitance probes and their calibration technique, respectively. Subramanyam Iyer, Hongder Chang and D. Jeffrey Lischer designed and constructed the optical fiber anemometer. D. Jeffrey Lischer also evaluated the performance of optical fiber sensors for measuring voidage.

5. Conclusions

During the course of this project, we have primarily developed new diagnostic techniques to measure the concentration and velocity of particles in dense suspensions, and we have tested these probes in the pneumatic transport of dense, cohesive plugs. Because the capacitance probes are directly applicable to other suspension flows such as pneumatic transport or fluidization, we are now helping a small business commercialize these probes, so other laboratories may benefit from the technique. In addition, we have carried out computer simulations of various generic configurations of rapid granular flows, which have brought insight into suspension flow regimes where particle collisions are important.

We wish to express our gratitude to the Department of Energy for making this research project possible.

REFERENCES

- Hanes D., Jenkins J. & Richman M., J. Appl. Mech. **55**, 969 (1988).
- Jenkins J., J. Appl. Mech., in press (1991).
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