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Polystyrene Latex Separations by Continuous Flow Electrophoresis on the Space Shuttle

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Abstract

The seventh mission of the Space Shuttle carried two NASA experiments in the McDonnell Douglas Astronautics Corporation continuous flow electrophoresis system. The objectives were to test the operation of continuous flow electrophoresis in a reduced gravity environment using stable particles with established electrokinetic properties and specifically to evaluate the influence of the electrical properties of the sample constituents on the resolution of the continuous flow electrophoretic device. Polystyrene latex microspheres dispersed in a solution with three times the electrical conductivity of the curtain buffer separated with a significantly larger band spread compared to the second experiment under matched conductivity conditions. It is proposed that the sample of higher electrical conductivity distorted the electric field near the sample stream so that the polystyrene latex particles migrated toward the chamber walls where electroosmosis retarded and spread the sample.

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1. INTRODUCTION

A continuous flow electrophoresis system (CFES) has been designed and built for use on the Space Shuttle by the McDonnell Douglas Astronautics Corporation (MDAC). A joint agreement between MDAC and the National Aeronautics and Space Administration (NASA), which shares the cost of developing and flying CFES, permits MDAC to maintain proprietary control over parts of their apparatus and biological sample materials and provides space on the CFES for NASA to conduct research into electrophoresis (*1*). The first MDAC space experiment was flown on the fourth mission of the Space Transportation System (STS-4) in June 1982 and processed two major samples: rat and egg albumin at high concentration and a proprietary tissue culture medium (*2*). On STS-6 in April 1983, MDAC expanded upon their first experiments by further increasing the quantity of sample processed. Two NASA samples were also flown on STS-6: a high concentration of hemoglobin and a lower concentration mixture of hemoglobin and a polysaccharide in barbitol buffer at pH 7.8. The purpose of the NASA experiment was to evaluate the influence of sample concentration on separation resolution. These NASA experiments showed an excessive broadening of the sample bands. The broadening was apparently caused by a difference of electrical conductivity between the sample and curtain buffer. (In preparation: R. S. Snyder, T. Y. Miller, P. H. Rhodes, B. J. Herren, J. L. Sloyer, L. H. Karr, and G. V. F. Seaman, "Continuous Flow Electrophoresis in Space.") This conclusion is supported by laboratory experiments which tested the proposed model of the phenomenon. The NASA experiments on STS-7 in June 1983 were intended to build upon the results obtained on STS-6.

Because MDAC changed the curtain buffer on STS-7 from a barbitol buffer (pH 8.3) to a propionate buffer (pH 5.2), it was not possible to perform a follow-up experiment using hemoglobin and polysaccharide as processed on STS-6. The change in pH would have resulted in both the hemoglobin and polysaccharide becoming positively charged and migrating toward the cathode. Under these conditions, the chamber configuration would have allowed a migration distance of only 3 cm before the sample collected on the cathodic membrane.

Polystyrene latex particles (PSL) were, therefore, chosen for separation on STS-7 since they are known to be negatively charged at pH 5.2 and can be produced in a range of sizes with different surface charge groups and surface charge densities. Data from the STS-6 NASA experiments demonstrated considerable band broadening when the sample conductivity was approximately three times that of the curtain buffer. These data, as well as prior ground-based data, provided the justification for the design of the STS-7 experiment which evaluated the relationships between the sample and buffer properties and the fractionation resolution.

1.1. Background

Strickler (*3*) and Hannig (*4*) developed continuous flow electrophoresis for the preparative fractionation of particles, partially because zone electrophoresis is limited by an inability to stabilize the free liquid media against buoyancy-induced convection. The electrophoretic separator consists of a very thin liquid curtain (0.15 cm or less) which transports the sample stream through an electrical field oriented perpendicularly to the sample flow through the chamber. The sample is collected in an array of collection tubes which span the width of the curtain at the bottom of the chamber. Since separation resolution depends on the intensity of the electrical field across the chamber and on the residence time of the sample in the field, considerable joule heating develops in the curtain electrolyte. On Earth, the temperature gradients generated in all three axes modify flow and particle migration through the chamber and degrade the separation.

The MDAC CFES flight instrument and several comparable electrophoretic separators were derived from a study begun in 1976 of the feasibility for commercial space manufacturing using continuous flow electrophoresis (*5*) and from experiments conducted with a laboratory chamber (*6*). A free-flow electrophoresis experiment, directed by K. Hannig, was flown on the Apollo-Soyuz Test Project (ASTP) in 1975. The purpose of that experiment was to study particle electrophoresis in a wide-gap separation chamber and to investigate the possibility of separating large quantities of biological cells (*7*). In 1977 NASA accepted a proposal to fly a small continuous flow electrophoresis apparatus built by the General Electric Company for the Space Processing Applications Rocket Program (*8*). However, to be effective, the experiments would have required more than the 5 min of microgravity provided by the rocket. Concurrently, research on the limitations to laboratory electrophoresis and the development of models of the fluid flow and particle movement was carried out at Marshall Space Flight Center and Princeton University (*9*). McDonnell Douglas Astronautics Corporation built several continuous flow electrophoresis systems for laboratory testing in 1980 and determined the requirements for protein separation of interest to at least one pharmaceutical company. The goal of the MDAC CFES in microgravity was to accomplish a significant increase in the quantity of materials that could be fractionated without simultaneously decreasing the resolution of separation. The CFES flight instrument was designed toward this goal, and NASA samples were selected that were compatible with the MDAC apparatus.

2. MATERIALS AND METHODS

2.1. Buffers

The curtain buffer was prepared from a 100× stock solution of 225 m*M* sodium propionate, pH 5.2, by 100× dilution with distilled water to give a 2.25 m*M* solution of pH 5.0 and conductivity of 140 ± 5 μmhos. Laboratory tests were initially performed with a nonionic surfactant, 0.05% w/v Brij 35 (polyoxyethylene lauryl ether 35) added to the sample and curtain buffer. Shortly before flight, however, it became necessary to remove the Brij from the curtain buffer. Since the sample latex had been selected according to their separation in buffer with Brij, the flight samples included Brij in the suspension medium but excluded Brij from the curtain buffer.

2.2. Sample

Monodisperse polystyrene latex (PSL) particles less than 1.0 μm in diameter were chosen to minimize sedimentation and eliminate any requirement for resuspending the sample during flight. These samples were supplied by Particle Technology, Inc., Bethlehem, Pennsylvania, and Interfacial Dynamics Corporation, Portland, Oregon. They were selected according to the mobility difference between their nominal values in the flight buffer, the stability of these mobility values, and their size differences as determined by transmission electron microscopy (TEM). All the particles considered for flight were evaluated in the propionate buffer at Lehigh University using the Pen Kem (Bedford Hills, New York) System 3000 unit. Three particle sizes were ultimately chosen, and two of the particle populations were dyed to enhance photographic detail and aid in experimental analysis.

The latex particles with the highest mobility (nominal diameter of 0.56 μm) were dyed red; the particles with the lowest mobility (nominal diameter 0.80 μm) were dyed blue. The particles with intermediate mobility (nominal diameter 0.30 μm) were not dyed. The latexes were then suspended in the curtain buffer containing Brij using a procedure of buffer exchange with filtration. The effluent buffer was monitored for conductivity and pH to determine when the buffer exchange had been completed. The concentration of each latex dispersion was determined gravimetrically, and each sample was evaluated microscopically for aggregation. Appropriate volumes of each latex were combined to yield equal concentrations for the final flight sample with the following properties: total latex concentration, 5.0%; pH, 5.6; and conductivity, 155± μmhos/cm. The conductivity of a second sample of PSL was increased approximately three times that of the initial sample to 455 ± 5 μmhos/cm using 0.10 *M* NaCl, while maintaining a total latex concentration of 5.0% by weight.

2.3. Electrophoretic Instruments

The CFES flight chamber (Fig. 1) consists primarily of two 0.08 cm thick polycarbonate plates which form a separation chamber 16 cm wide, 120 cm long, and 0.3 cm thick. These plates are also the interior walls of a cooling jacket which cover each broad chamber face. The 0.2-cm wide platinum electrodes extend the length of the chamber and are housed in the cooling jacket diagonally across from each other to provide the electrical field which covers the length of the chamber. The electrodes, which are covered with a proprietary porous membrane, are in contact with the separation chamber via slots cut into the chamber plates. The cooling fluid contains the same electrolyte as the separation chamber fluid. Bubbles formed at each electrode are removed by cooled electrolyte which is circulated, via a serpentine passageway, from the bottom to the top of the chamber. Rectangular struts used to form the serpentine passage also provide some support to the thin separation chamber plates. The sample enters the chamber through a thin-walled glass tube of 0.1 cm inside diameter located 11 cm from the bottom of the chamber where the curtain buffer also enters. A syringe pump inserts the sample while the curtain and coolant electrolyte fluids are driven by rotary positive displacement pumps. The buffer and separated sample fractions exit at the top of the chamber through a collection array of 197 Tygon tubes (0.068 cm i.d., 0.078 cm o.d.) which spans the width of the chamber.

A laboratory electrophoresis chamber (Fig. 2) was built by MDAC as a prototype of the CFES flight instrument and for use in comparison separations. The lower portion of the main separation chamber is 6.0 cm wide and 0.15 cm thick. Nine centimeters from the top of the chamber,

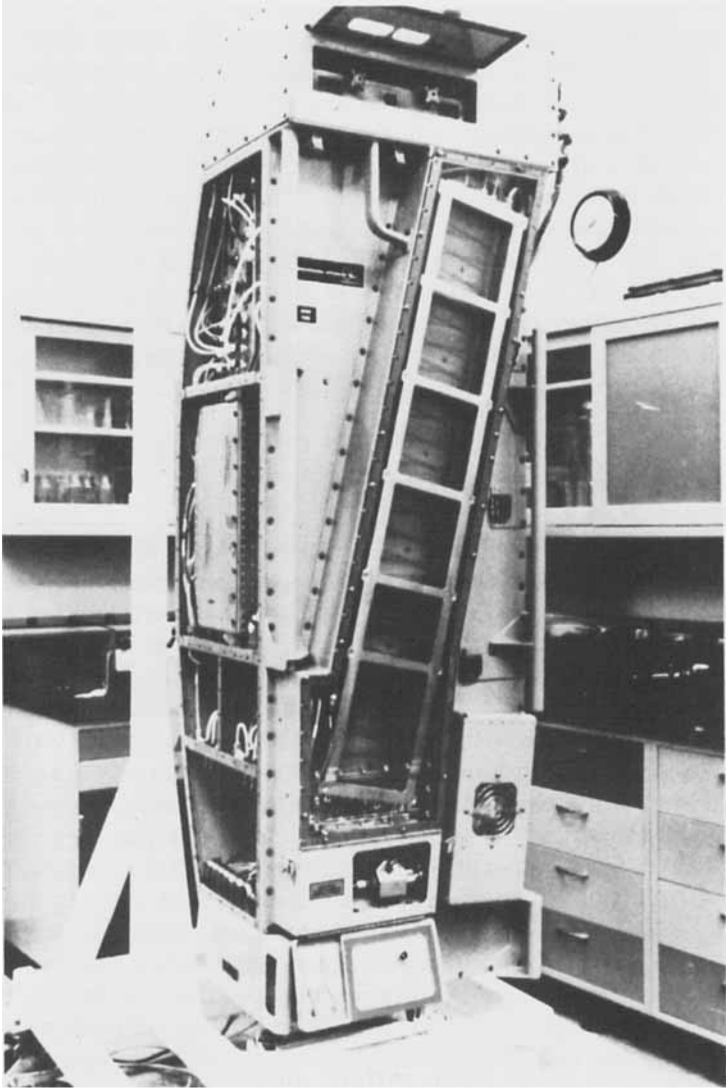


FIG. 1. Photograph of MDAC space continuous flow electrophoresis systems (CFES).

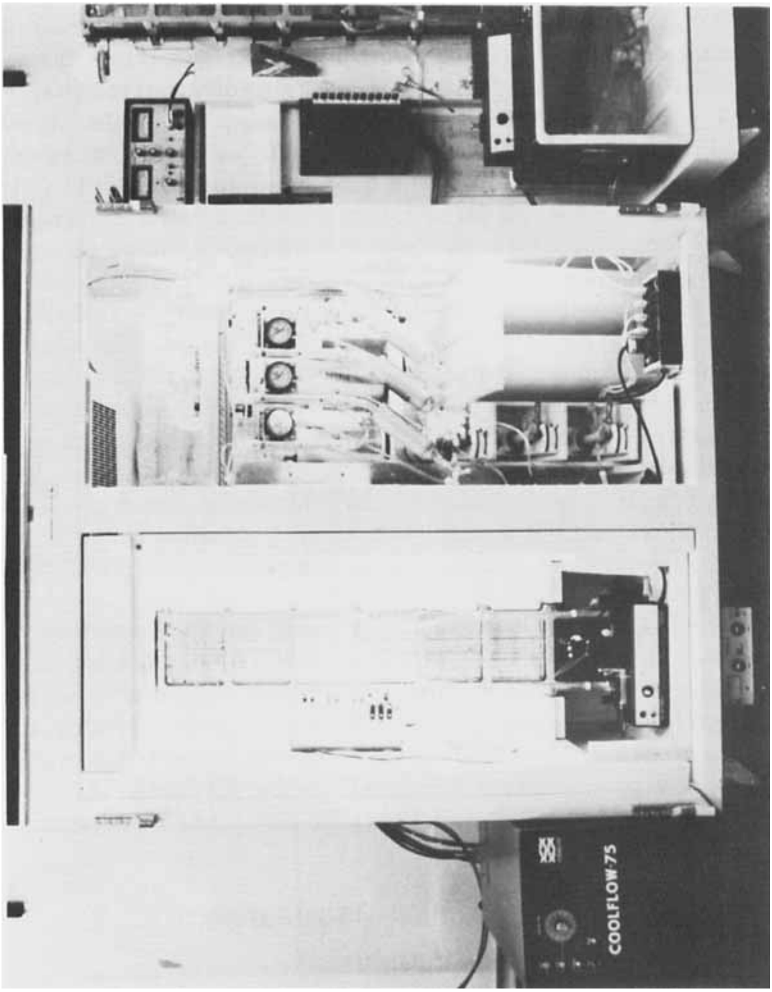


FIG. 2. Photograph of MDAC Laboratory CFES.

the width of the channel flares from 6.0 to 16.0 cm to accommodate the 197 tube collection system.

The Beckman Continuous Particle Electrophoresis Device (CPE) (*3*) consists of two Plexiglas plates which form a separation chamber 4.5 cm wide, 30.0 cm long, and 0.15 cm thick. Only the front plate contains a cooling chamber which is used to remove heat generated during a separation and to maintain stable temperature gradients in the chamber. The back plate houses the 30-cm long platinum electrodes in slots positioned on either side of the chamber. Cellulose acetate membranes partition the electrode chambers from the separation chamber. Electrode buffer is circulated by a centrifugal pump from the electrode reservoir to a pressure bottle and then through the electrode chambers where electrolysis products are removed. The curtain buffer is pumped by a variable speed peristaltic pump to a constant level reservoir and allowed to flow by gravity through a flowmeter and then into the chamber through a port located approximately 1.5 cm from the top of the chamber. The curtain buffer undergoes laminar flow down the chamber and exits through 48 stainless steel ports (0.1 cm i.d.) arranged laterally across the bottom of the chamber. This allows each port to receive a 0.1-cm slice of the curtain as well as any separated sample located in that region of the curtain. A syringe pump injects the sample, as a continuous stream, into the curtain buffer through a stainless steel sample insertion port (0.03 cm i.d.).

A window, located approximately 5.0 cm above the collection port array, with a millimeter scale for the measurement of sample band widths and migration distances (deflections), facilitates comparisons between the CPE and MDAC instruments. The CPE is also equipped with a cross-section illuminator (*10*) for viewing particle distributions horizontally through the chamber, making it possible to see the "crescents" which result from the combined effect of Poiseuille flow and electroosmosis.

3. RESULTS AND DISCUSSION

3.1. Separation Characteristics and Laboratory Separations

Photographic tests demonstrated that latexes in the chosen size range are highly visible at concentrations of 0.1% solids and above. Experiments conducted in the Beckman CPE and the MDAC ground-based apparatus at nominal flow rates, using a 10% concentration of particles, showed some droplet formation and some plugging in the narrow sample insertion tube. Since the sample had undergone buffer exchange to remove emulsifiers and surfactants, the droplets observed at the 10% concentration could have resulted from particle aggregation. In experiments using a 5% particle concentration, the sample showed no aggregation or sedimentation problems and was used for subsequent experiments.

Initial ground-based experiments to test the separability of the PSL samples were conducted using the Beckman CPE. Different concentrations of samples prepared in buffer that matched or exceeded the curtain buffer conductivity were run at different residence times and electric field conditions. Photographs of the particle streams made using the CPE and front illumination (Figs. 3A and 3B) show comparisons of the stream deflections and particle band widths for the matched and unmatched conductivity samples.

Figures 3(C) and 3(D) show the crescent profiles of the sample streams obtained using the cross-section illuminator attached to the CPE. The cross-section illuminator allows one to observe the deflection, band width, and shape of the separated PSL sample band. The profiles, in the form of crescents, provide useful information on fluid dynamic phenomena occurring in the transverse plane of the chamber during an electrophoresis run, i.e., electroosmosis and Poiseuille flow, which distort the sample bands from their original symmetrical input geometry.

Comparison of the deflections and band widths for the conductivity-matched and -unmatched samples clearly shows increased band spread (in the form of elongated crescents) in the unmatched conductivity samples. The crescents formed by the matched conductivity samples are much smaller and exhibit less sample spread in the direction of the thickness (transverse plane) of the chamber. The shape and direction of the crescents also provide important information concerning deflections and separability of the sample. For instance, the orientation of the crescent specifies the value of the wall charge relative to that of the sample species, and an undistorted sample cross-section indicates that the sample and wall have equivalent electrokinetic properties.

The initial ground-based studies were conducted with curtain buffers and samples in propionate buffer containing Brij. However, prior to flight, MDAC found it necessary to change the curtain buffer formulation by excluding the addition of Brij from the curtain buffer. Laboratory tests in both the Pen Kem 3000 and the CPE demonstrated that the removal of Brij from both the sample solution and curtain buffer resulted in an increase in the mean mobilities for all three samples while decreasing the difference in mean mobility between each of the samples. This was observed in the CPE as crescent overlap (Fig. 3C). Since it was

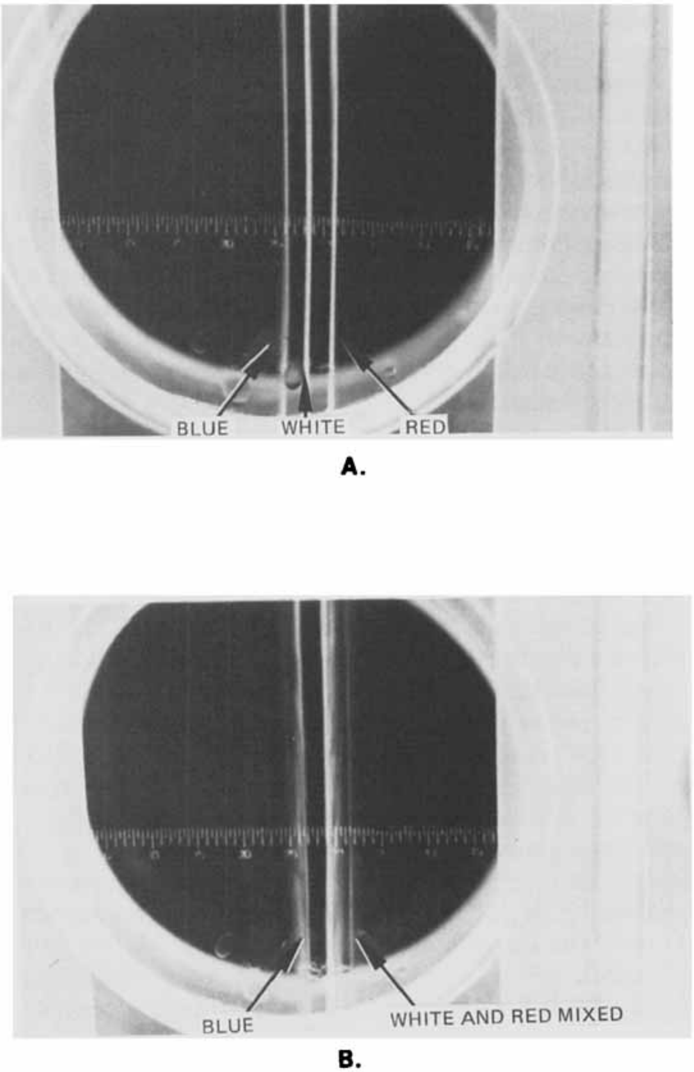
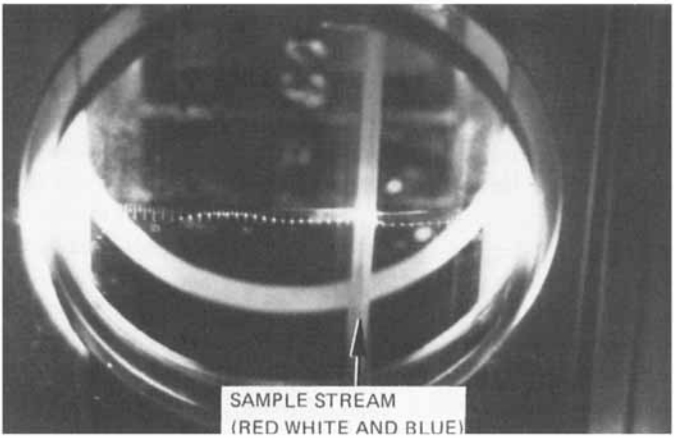
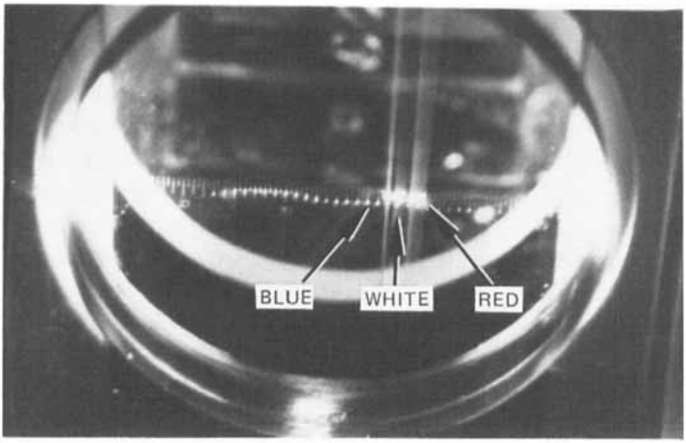


FIG. 3. Deflections of polystyrene latex in the Beckman continuous particle electrophoresis (CPE) system. The PSL streams are denoted as red (0.56 μm), white (0.3 μm), and blue (0.8 μm). Figure 3(A) shows the separated PSL sample streams photographed through the viewing window of the CPE using front illumination. Figure 3(B) shows a comparison of the separation of PSL streams under the same experimental conditions as those in Fig. 3(A)



C.



D.

except that the suspending buffer for the sample was 3× the conductivity of the curtain buffer. Figure 3(C) demonstrated the poor sample band resolution obtained when Brij 35 was removed from the sample. Figure 3(D) is a photograph obtained using the cross-section illuminator attached to the CPE. The crescents formed due to the interactions of electroosmosis and Poiseuille flow are visible for each separated sample component.

not possible to obtain separation under these conditions, tests were conducted to determine the separability of the sample population using propionate buffer with Brij for the sample suspension media while excluding Brij from the curtain buffer. The sample was shown to retain its separability in tests run in the CPE at 1.5 min residence time.

Further experiments were conducted in the CPE to closely approximate the residence time for the space flight experiment (8 min). Figure 3(D) shows the separated bands in cross section obtained from a sample containing Brij in the sample suspension media that had been dialyzed with curtain buffer from which Brij had been excluded. Results indicated that the Brij would continue to modify the PSL surface properties during the 8-min flight residence time in a curtain buffer that did not contain Brij. It was agreed that the NASA samples would be prepared as before, in Brij, and that separation in microgravity would be carried out using a curtain buffer that did not contain Brij.

The mobilities of the polystyrene latex samples slowly increased during storage in the propionate solution containing Brij, attaining, just before flight, the mobility distribution shown in Table 1. There was insufficient time to characterize the entire system propertly, and, although the mobility increases were associated with an increase in fluid pH, only the PSL samples could be manipulated since the curtain buffer was defined by MDAC. Most of the emulsifier associated with the PSL samples was removed during the propionate buffer exchange, and it is possible that trace amounts remaining in the particles slowly reentered the buffer. Similarly, the oil-soluble dyes used to stain the PSL sample were not permanent since they also slowly leached into the buffer and had to be removed by repeated dialysis. However, the major increase in the sample mobilities occurred when Brij was removed from the curtain buffer while the Brij was retained in the sample buffer. These measurements were made by diluting the original Brij buffer with non-Brij buffer. Mobility measurements of the PSL sample suspended in buffer containing Brij,

TABLE 1

Measured Mobility of Latex Samples in Buffer with Variable Amounts of Brij

	Anodic mobilities (mV^{-1} s^{-1} cm) at 25°C		
Dilution	Blue	White	Red
0	0.9	1.8	3.2
10:1	1.5	1.8	3.2
1000:1	1.6	2.4	3.5

diluted by curtain buffer without Brij (Table 1), showed that the mobilities increased steadily as the Brij became more dilute, indicating desorption of Brij from the sample. The undiluted sample represents the starting condition of sample as it entered the CFES chamber. The tenfold dilution represented an intermediate condition and the thousandfold dilution approximated conditions near the collector. These final mobility values also agreed well with mobilities of the PSL sample collected during the flight experiment.

3.2. Separations in Microgravity

The prepared samples were loaded into the MDAC flight syringes approximately 48 h before launch on June 18, 1983. The experiments were carried out on the second and fourth days into the flight for the unmatched (Sample 1) and matched (Sample 4) conductivities, respectively. The only experiment anomaly, a pressure difference between the anode and curtain fluids, was equalized before the separation began.

The PSL mixture was initially sent through the CFES with no applied electric field to establish the zero-voltage flow conditions in space. This sample was not collected but was photographed at three locations: sample insertion (10 cm mark), middle of the chamber (near the 70 cm mark), and the top of the chamber (120 cm). The electric field was then turned on, the flow stabilized, and the sample inserted again. The separating sample was photographed at the three chamber locations indicated above, and a portion was collected into the trays for later analysis.

The collection trays containing 197 polyethylene sacks of approximately 1.8 mL capacity were recovered from the Space Shuttle soon after landing. For each run the collected volumes of each sack were uniform within 10% with only one empty sack, due presumably to a plugged collection tube. The conductivity and pH profiles were characteristic of those obtained in ground-based experiments, with the conductivity increasing and the pH decreasing from cathode to anode. Each sample fraction was inspected visually for PSL particles. An increased spread observed in the unmatched conductivity sample was accompanied by a large shift in the migration of the white and red PSL. Alternate fractions of the sample were sent to Lehigh University for analysis of particle mobility and precise measurement of particle distribution by TEM, and the remaining fractions were retained at MSFC.

Although the distribution of color in the sample collection trays

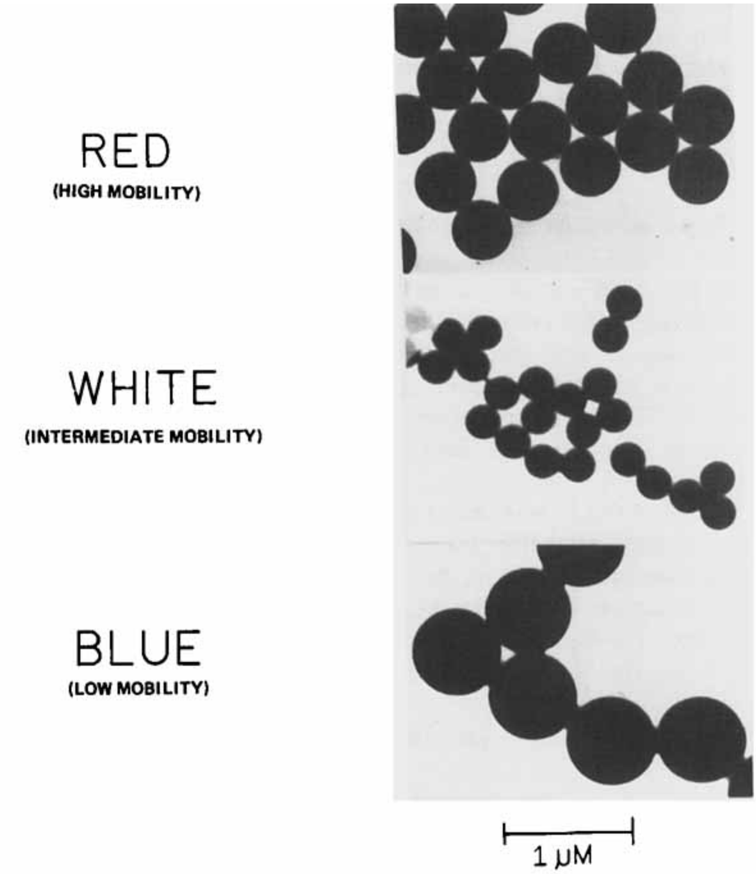


FIG. 4. Transmission electron micrographs of latexes used as sample in CFES on the STS-7 Mission.

showed the band spreads, more definitive information regarding the success of the separation was required. The relative particle concentration of the three latexes in the collected fractions was determined by TEM (Fig. 4). Between 800 and 3000 particles were counted for each fraction evaluated. The absolute weight percent of the fractions was determined by measuring the turbidity of the samples on the Pen Kem System 3000 and comparing the results to previously prepared calibration curves for the latex in question. For situations where electron microscopy revealed a significant amount of more than one size latex, it was assumed that each latex made a linear contribution to the total sample turbidity based on the relative concentration. The relative and absolute concentrations were correlated to give a detailed illustration of the separation for the matched and unmatched conductivity experiments.

Figure 5 clearly shows the differences between the matched (A) and unmatched (B) conductivity cases. The matched conductivity run shows more overlap than predicted, possibly due to sample wavering, but the latexes did separate into easily recognizable peaks. For the unmatched conductivity case, the sample spreading and overlap was very severe. In addition, the red latex stream shows greater distortion than the white and blue latex streams, having no clearly defined maximum concentration and a very wide collection range. Also, the increase in the average particle displacement for all three latexes is clearly illustrated.

The photographs taken in space show the separation of the polystyrene latexes at a specific location and time. Figure 6 shows a sequence of the PSL with matched conductivity from its insertion at the bottom of the figure to its collection at the top. The slight curvature of the sample streams near the collection is a characteristic of the CFES instrument since it occurred at zero voltage and was also observed on STS-6.

Figure 7 shows a series of photographs of the unmatched sample conductivity (left side) and matched sample conductivity (right side). These photographs are of the separated latexes just before entering the collection tray at the top of the CFES. The band distortion and spreading of the PSL samples when the conductivities of the samples and curtain were not matched is evident from the photographs and was confirmed by analysis of the collected fractions. Sample wavering, as indicated by a change in transverse band position with time, is also seen in all flight photographs. This wavering increased the collected spread for both samples as shown in Fig. 8. The sample wavering is probably due to the bubbles observed at the electrodes and their influence on the thin chamber walls or electrode membrane. Postflight inspection revealed a hole in the anodic membrane midway up the chamber, but its impact on

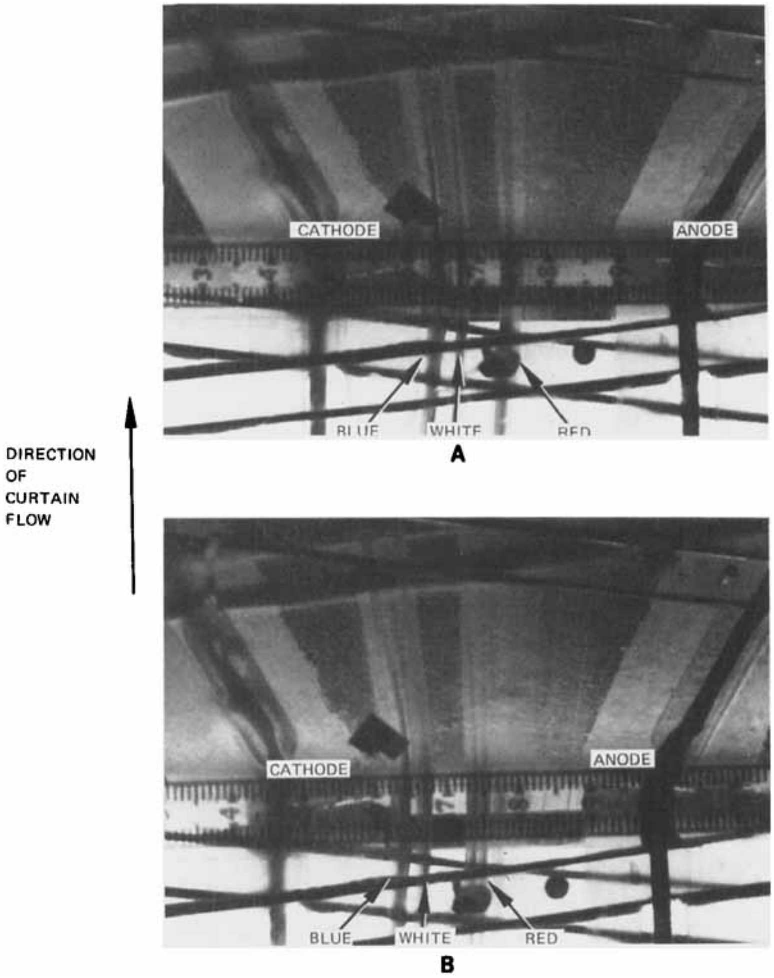


FIG. 5. Deflections of polystyrene latex photographed near the flare in the McDonnell Douglas Laboratory electrophoresis system.

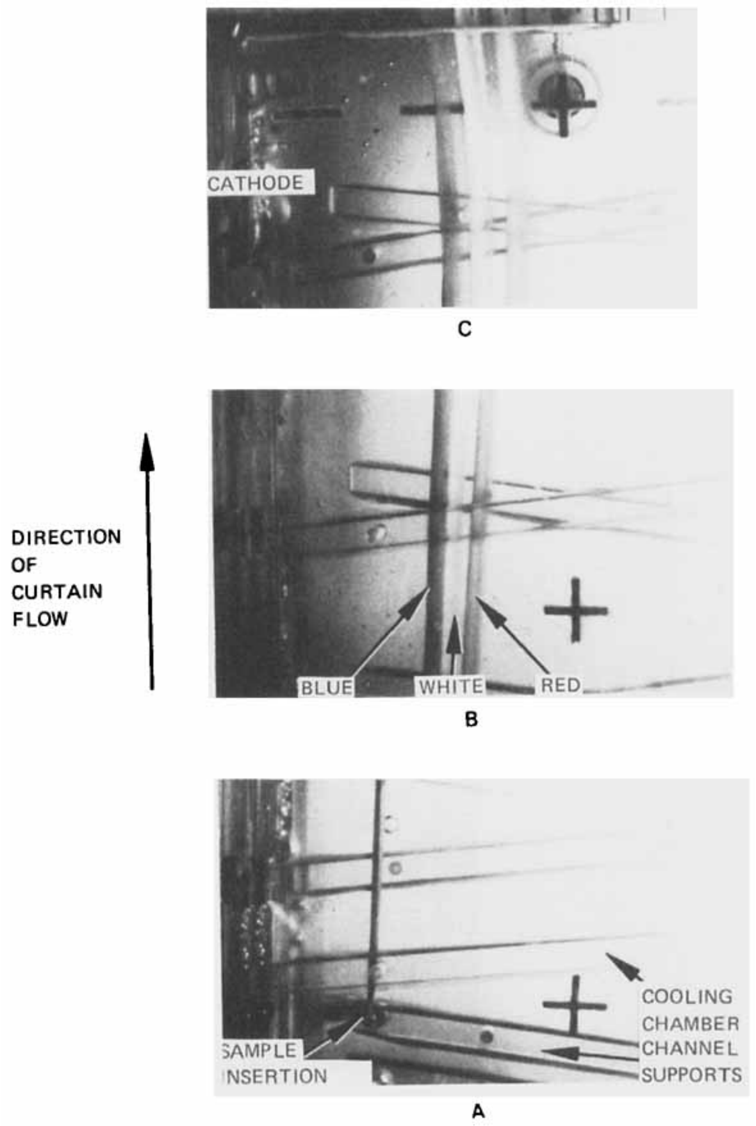


FIG. 6. Flight photographs of matched conductivity polystyrene latex sample at (A) input (11 cm), (B) chamber center (70 cm), and (C) collector (120 cm).

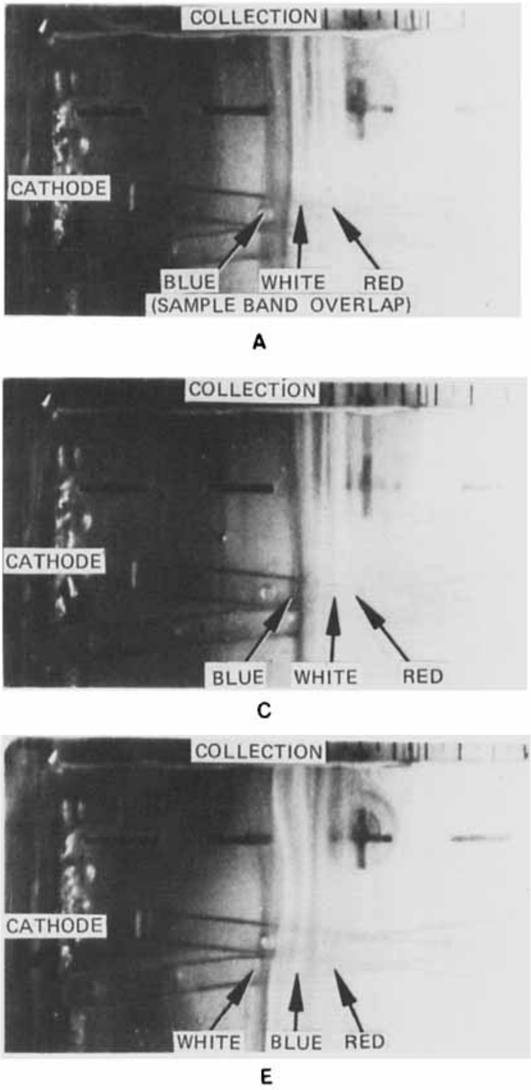
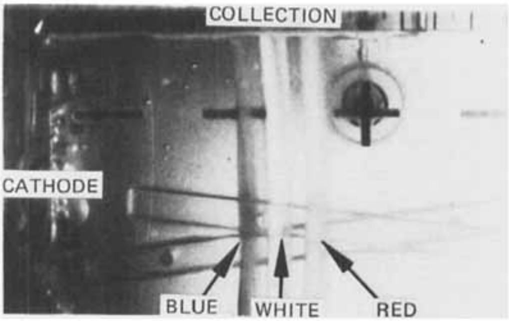
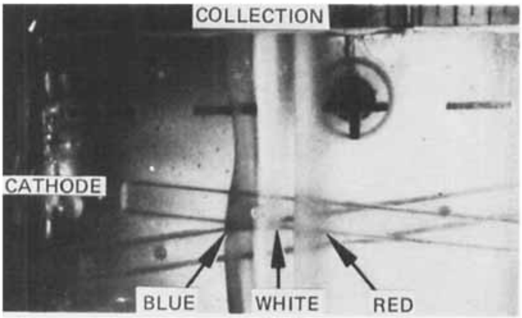


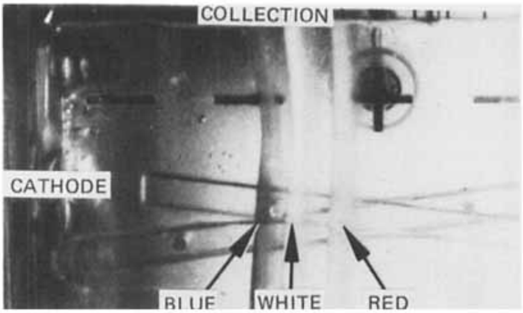
FIG. 7. Flight photographs taken near the CFES collection ports of deflections of unmatched sample/curtain buffer conductivity conditions (A, C, and E) and matched sample/curtain buffer conductivity conditions (B, D, and F). The separations obtained



B



D



F

under matched conductivity conditions show discrete band formation while the separations resulting from unmatched conditions show poorly defined band structure and extensive sample overlap.

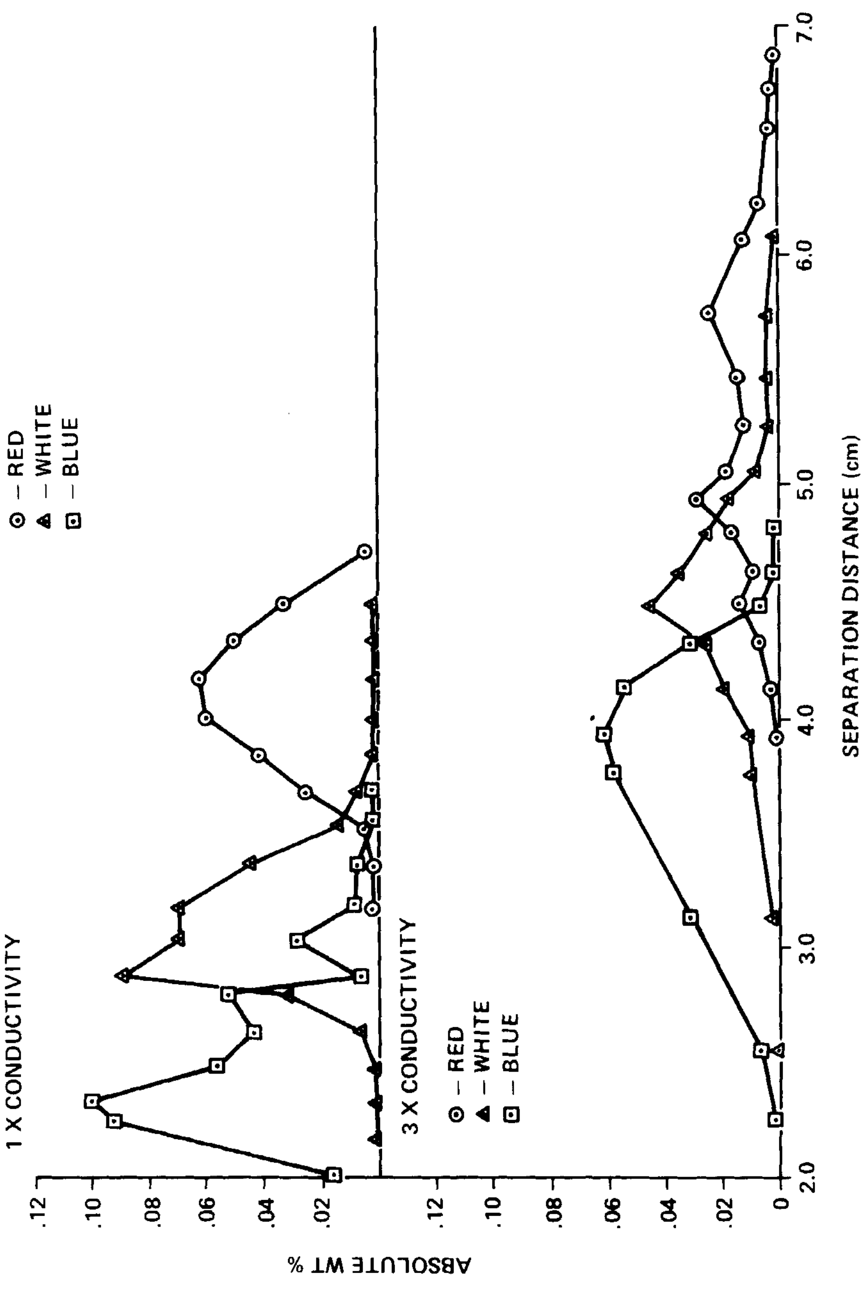


FIG. 8. Distribution of PSL in collection system.

separation is not known. Figure 9 shows the zero-voltage sample stream and separating PSL near the 70-cm mark; note that deflections of both samples are comparable.

It is proposed that the increased spreading in the unmatched sample was a result of the sample first being displaced away from the chamber center plane by the electric field in the vicinity of the sample, where a conductivity boundary exists, and then being spread laterally by the action of viscous flow and electroosmosis. To test this reasoning, the migration distances of the leading and trailing edges of the sample streams were measured from Fig. 7 and calculations then made to determine the transverse spreading necessary to produce these results. Data from these calculations are given in Table 2.

Based upon calculations made from the measurements of the sample stream in the photographs, the cross section shown in Fig. 10 graphically shows the results of the spreading in both transverse and lateral directions. While the calculations shown in Table 2 are based solely on the relative positions of the observed sample bands, these results nevertheless agree very closely with the measured mobilities of the individual particles shown in Table 1. The calculations also show that the unmatched sample occupied 70% of the chamber thickness while the matched sample occupied 60%. These findings indicate that the sample did indeed spread in the chamber thickness into marginal zones where lateral flows predominate.

It is also interesting to observe that the band spreading occurred as soon as the sample was inserted into the chamber. Figure 11 shows a sequence of photographs of the sample insertion point with unmatched conductivity on the left and matched conductivity on the right. This is supported by some ground experiments recently completed which will be reported in a subsequent publication.

TABLE 2
Calculated Mobility of Latex Samples during the Flight Experiments

	Mobility (mV^{-1} s^{-1} cm) at 25°C	
Item	For matched conductivity	For mismatched conductivity
Wall mobility	1.2	1.3
Blue PSL mobility	1.5	1.8
White PSL mobility	2.3	2.6
Red PSL mobility	3.2	3.2

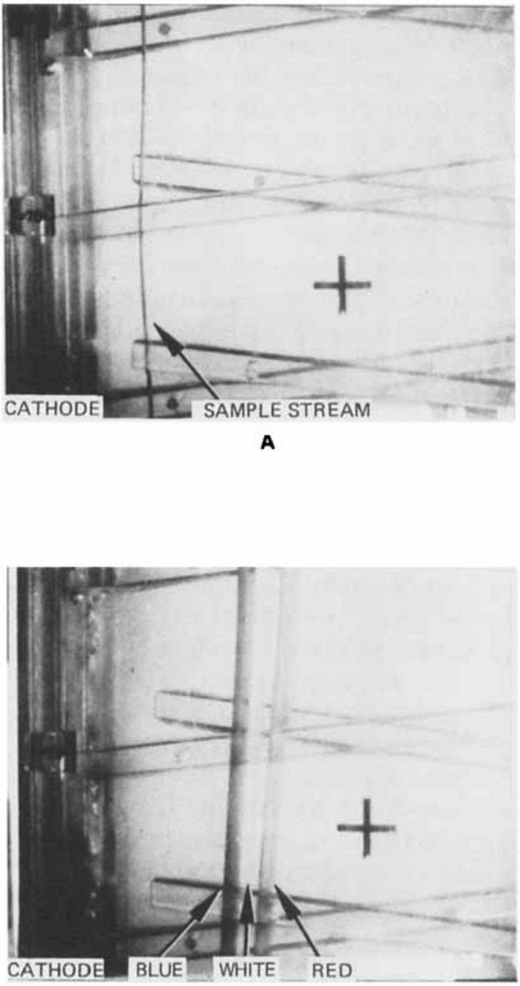
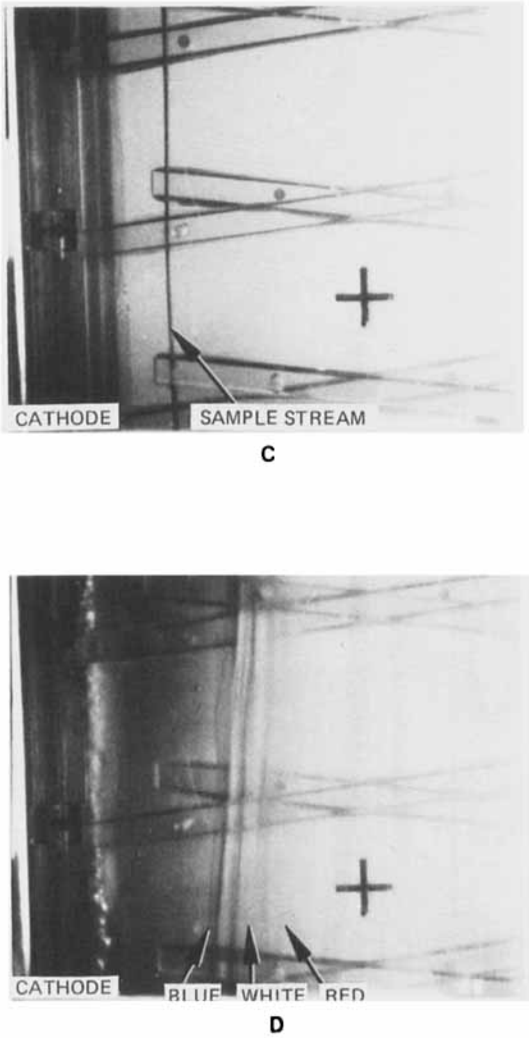
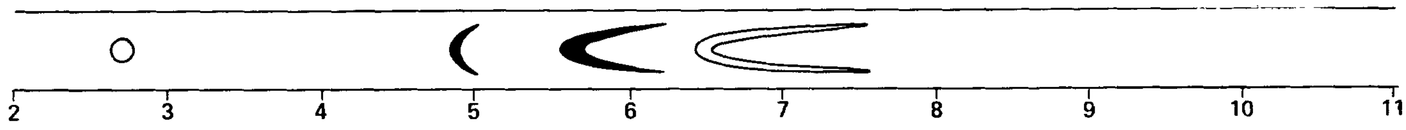


FIG. 9. Comparisons of matched (A, B) and unmatched (C, D) samples at the 70-cm mark



for zero voltage (A, C) and 27 V/cm (B, D).



a. SAMPLE CROSS SECTIONS FOR MATCHED SAMPLE

b. SAMPLE CROSS SECTIONS FOR UNMATCHED SAMPLE

FIG. 10. Sample cross sections for matched and unmatched conductivity samples.

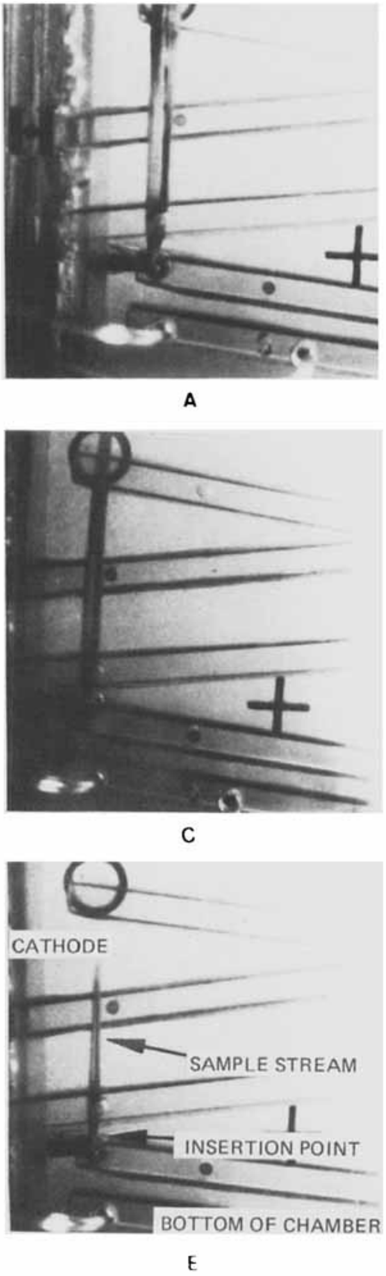
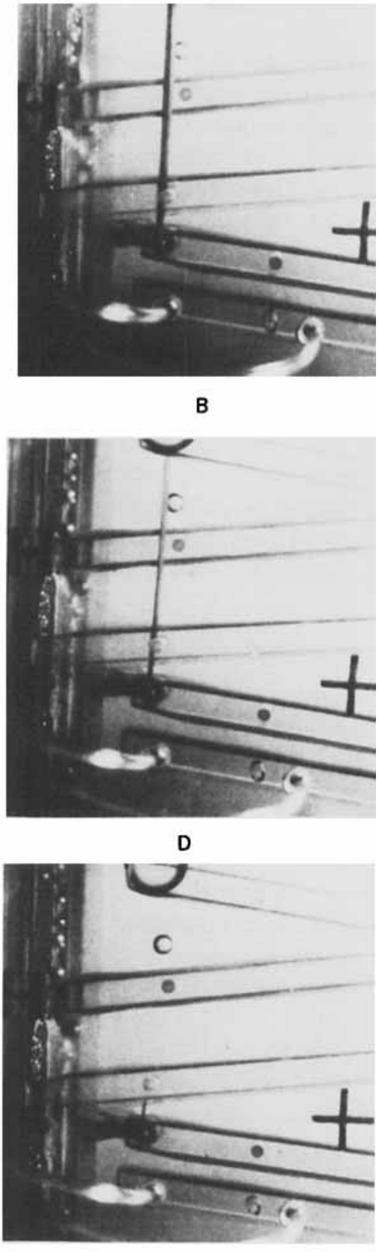


FIG. 11. Flight photographs of sample insertion for unmatched sample conductivity (A, C,



and E) and matched sample conductivity (B, D, and F).

4. DISCUSSIONS AND CONCLUSIONS

The results from the two NASA polystyrene latex experiments on STS-7 clearly confirm the importance of matching the electrical conductivity of the sample solution with the curtain buffer conductivity. Laboratory experiments also confirmed the increased band spread when the conductivity is not matched, and the cross-section illuminator showed that the extension of the crescents was the primary cause of broadening. Converging components of the applied electric field at the sample band can explain sample ribbon formation observed in laboratory electrophoresis chambers and the migration of the sample perpendicular to the electrophoretic mobility. Thus, the flight results, laboratory measurements, and a model support each other qualitatively.

It is planned to develop a mathematical model of sample stream distortion under different conditions of sample conductivity and concentration to complete the analysis of sample stream broadening during electrophoresis. Additional effort is also needed to determine the role of particle concentration, if any, in free-flow electrophoretic separations. Laboratory experiments clearly show limitations that are not entirely due to droplet sedimentation.

ABBREVIATIONS

ASTP	Apollo Soyuz Test Project
Brij 35	polyoxyethylene lauryl ether 35
CFES	continuous flow electrophoresis system
CPE	continuous particle electrophoresis
MDAC	McDonnell Douglas Astronautics Corporation
NASA	National Aeronautics and Space Administration
PSL	polystyrene latex
STS	space transportation system
TEM	transmission electron microscopy

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