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Mixing of Supersonic Streams
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Abstract

The Strutjet approach to Rocket Based Combined Cycle (RBCC) propulsion depends upon fuel-rich flows from the rocket nozzles and turbine exhaust products mixing with the ingested air for successful operation in the ramjet and scramjet modes. It is desirable to delay this mixing process in the air-augmented mode of operation present during low speed flight. A model of the Strutjet device has been built and is undergoing test to investigate the mixing of the streams as a function of distance from the Strutjet exit plane during simulated low speed flight conditions.

Cold flow testing of a 1/6 scale Strutjet model is underway and nearing completion. Planar Laser Induced Fluorescence (PLIF) diagnostic methods are being employed to observe the mixing of the turbine exhaust gas with the gases from both the primary rockets and the ingested air simulating low speed, air augmented operation of the RBCC. The ratio of the pressure in the turbine exhaust duct to that in the rocket nozzle wall at the point of their intersection is the independent variable in these experiments. Tests were accomplished at values of 1.0, 1.5 and 2.0 for this parameter. Qualitative results illustrate the development of the mixing zone from the exit plane of the model to a distance of about 10 rocket nozzle exit diameters downstream. These data show the mixing to be confined in the vertical plane for all cases, The lateral expansion is more pronounced at a pressure ratio of 1.0 and suggests that mixing with the ingested flow would be likely beginning at a distance of 7 nozzle exit diameters downstream of the nozzle exit plane.

Introduction

The Rocket-Based Combined Cycle (RBCC) propulsion system attempts to improve the performance of launch vehicles throughout the entire launch trajectory and make highly reusable launch vehicles a reality. The Strutjet RBCC concept consists of a variable geometry duct with internal, vertical struts that function in ducted rocket, ramjet, scramjet, and pure rocket modes¹. These struts have rocket and turbine exhaust nozzles imbedded within them. As shown in Figure 1, the four primary rocket flows exit at the end of the strut with three turbine exhaust nozzles in between them. The Strutjet is designed to mix the fuel-rich flows (rocket and turbine exhaust gases) in the vertical direction before significant combustion occurs with the ambient air. Only after the hot fuel-rich exhaust flows have mixed should combustion with the ingested air begin. The key issue under investigation is to understand and subsequently control the mixing of the exhaust gases of the rocket and turbine nozzles. Optimum performance of the (sc)ramjet mode occurs when proper mixing of the exhaust gases delays heat release in the duct until some desired location. The exhaust products are then expanded through the nozzle provided by the engine.

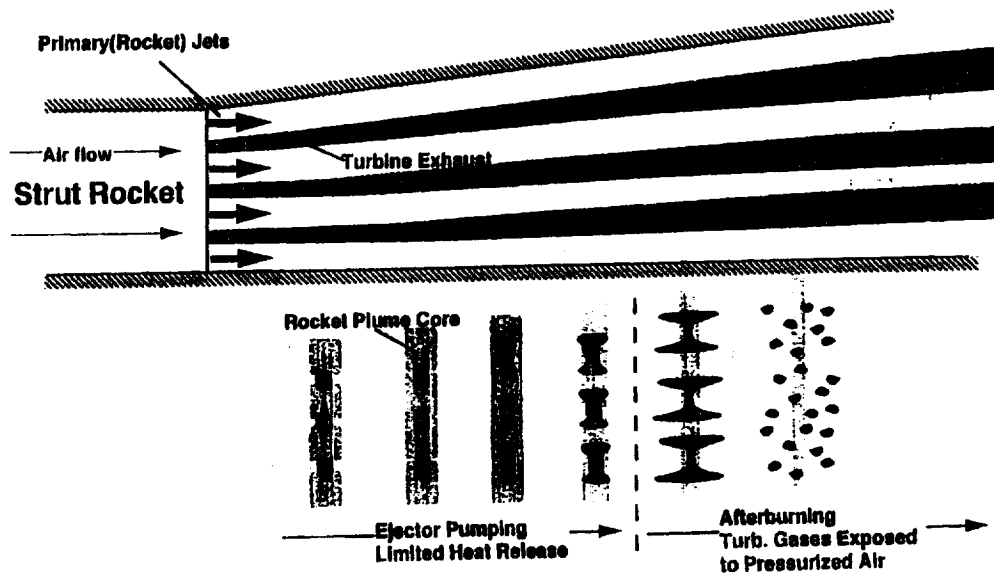


Figure 1. Strutjet concept

The full-sized Strutjet has many rocket nozzles with turbine nozzles between them, as in Figure 1. The $\frac{1}{6}$ th scale model used for testing in this project has just one turbine nozzle between two rocket nozzles. Figure 2 shows the scaled Strutjet in the duct.

The two rocket nozzles receive heated air from a system consisting of a tank with a volume of 524 cubic feet which is pressurized up to 2500 psi to supply a total airflow of 4 lbm/s at 600 psi. A 240 kW electric heater is used to heat the air to 760°R at the model. The turbine nozzle is supplied with a 0.1 lbm/s flow of CO₂ at 90 psi and heated to 760°R through a water bath- and a 12 kW electric heater.

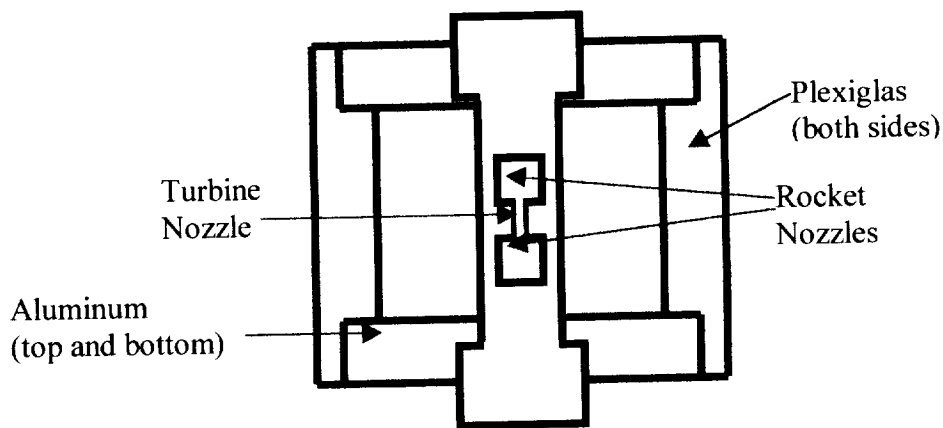


Figure 2. Scaled model inside duct.

The full scale mixing process is modeled based upon similitude of the convective Mach Number² between the turbine exhaust and rocket nozzle flows. This is achieved in the cold flow test by use of hot (760°R) air as the rocket exhaust simulant and hot (760°R) carbon dioxide as the turbine exhaust gas simulant³.

The measure of the mixing process is achieved through use of Laser Induced Fluorescence (LIF)³. The carbon dioxide gas is seeded with laboratory grade acetone. The acetone vapor is excited at a wavelength of 266 nm and the

fluorescent signal is emitted over a wide spectral range (~350 nm to 550 nm). The fluorescent signal will be collected over a bandwidth of 300-495 nm, eliminating interference from scattered laser light. Acetone fluorescence is linear with respect to incident laser intensity and acetone mole fraction⁴. Recently, it was discovered that acetone fluorescence also has a significant temperature dependence⁵. This limits the quantitative interpretation of the images to a comparison between the different measurements, rather than an absolute measurement of concentrations. ((Collision quenching of acetone fluorescence is also intra molecular⁴. The fluorescence is, therefore, independent of temperature and local gas composition. Thus, quantitative information is readily obtained from the collected images.)))

The acetone fluorescence has a lifetime of less than 4 nanoseconds. Acetone also phosphoresces at wavelengths similar to the fluorescence, albeit at a much greater lifetime of about 200 microseconds. The phosphorescence interference is rendered negligible by gating the intensified camera around the laser pulse (10 ns) at 13 nanoseconds. This also eliminates background interference

The Nd:YAG laser output of 1064 nm is frequency quadrupled to produce a 266-nm laser beam. The 1064 nm and 532 nm components of the beam will be separated into a beam dump while the 266-nm beam is sent to the test section. The beam is formed into a laser sheet approximately 3 inches high and 500 micron thick by a convex and a cylindrical lens. The beam then passes through a 4"x4" fused silica window into the duct. The beam traverses the model cross section of concern and passes through the Plexiglas sidewall on the other side. (Figure 3)

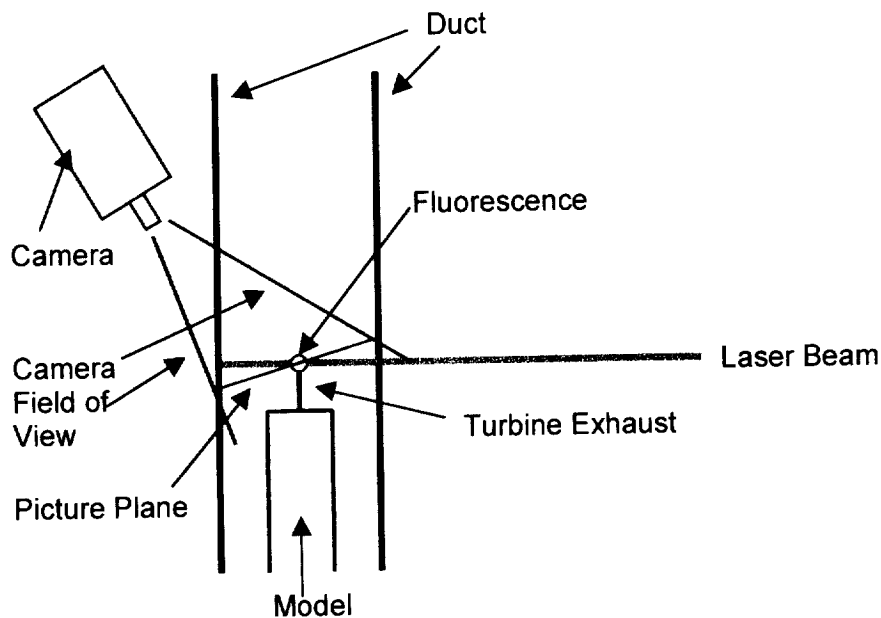


Figure 3, Optical Diagnostic Setup

The acetone fluorescent signal is observed by a Princeton ICCD camera. The intensity of the fluorescence is directly related to the acetone concentration in the flow.

Results and Discussion

The model in test has a rocket area ratio of 4.65 and the turbine exhaust nozzle area ratio of 1.184. The turbine exhaust nozzle is oriented in the vertical plane and intersects the rocket nozzle wall at an area ratio of 2.987. This is to promote mixing in the vertical direction. (Figure 4).

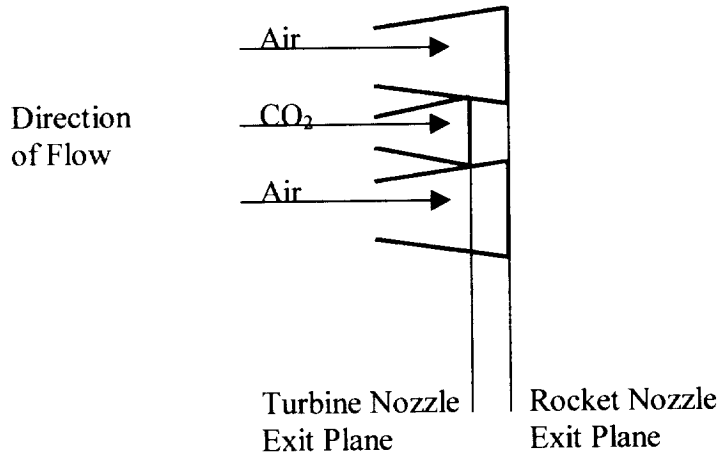


Figure 4 Rocket and Turbine Nozzle Exit Planes (Side View)

The exit plane of the turbine is approximately 0.25 inches upstream of the rocket nozzle exit plane. The pressure ratio of the two flows at the point of intersection was chosen as an independent variable in exploring the flow behavior. The pressures at the point of intersection were determined from the measured plenum pressures for each nozzle and assuming an isentropic flow with the known gases through an area ratio as determined from the as-built measurements of the model. The test matrix was as shown in Table 1.

Table 1 Test Matrix

Press. Ratio	Exit Plane	Laser Beam Location				
		0.5 Inch	1.5 Inch	2 Inch	7 Inch	10.25 Inch
2.0	X	X	X	X	X	X
1.5	X	X	X	X	X	X
1.0	X	X	X	X	X	X

The turbine exhaust plenum pressure was held at approximately 91 psia and the rocket plenum pressure was set at 275 psia, 366 psia, and 550 psia respectively to achieve these test conditions. This resulted in a calculated pressure of 26.2 psia at the turbine exhaust intersection plane and 13.1, 17.4, and 26.2 psia at the rocket nozzle intersection plane respectively.

The Spectra Physics Nd:YAG laser power was measured at 85 millijoules in the UV (266 nm) entering the window to the test section. Figures 5 through Z present the qualitative images obtained from the most recent set of experiments.

Figure 5 presents the images from the test condition of rocket to turbine pressure ratio of 2.0. Figure 5 a shows the condition at the exit plane. The high intensity image indicates the high concentration of acetone in the turbine exhaust flow at that location. Since the pressure in the turbine exhaust at the plane of intersection is greater than that in the rocket nozzle the flow is seen to “spill over” at the top and bottom of the image indicating the initiation of vortical flow at that location. Figure 5 b is the image at 1/2 inch downstream of the exit plane. Here, the vertical orientation of the turbine exhaust (core) flow is still evident. The top and bottom of the core flow show lateral spreading becoming more exaggerated. At 2 inches downstream, (Figure 5 c) flow structure has changed to a more circular configuration, but is still relatively well confined within the rocket flow field and not showing signs of mixing with the ingested flow.

Figure 6 presents the images from the test condition with the pressure ratio of 1.5. The exit plane still exhibits the “spillage” at the top and bottom of the intersection with the rocket nozzle (Figure 6 a). We observe that the flow

loses its vertical orientation more rapidly as the core flow appears to be more nearly square at a distance of ½ inch downstream (Figure 6.b). At two inches (Figure 6 c), the core flow retains its square shape and still appears to be within the rocket flow field and not yet interacting with the ingested flow.

Figure 7 presents the images at a pressure ratio of 1.0 At the exit plane (Figure & a), the core flow has the rectangular image and the evidence of “spillage” has disappeared as expected. The flow appears to be spreading in the lateral direction more rapidly than in the previous two cases (Figures 7 b and 7 c)

Conclusions

The qualitative results suggest that the goal of delaying mixing of the fuel-rich turbine exhaust with the ingested air is best accomplished for the selected configuration by maintaining a pressure at the turbine exhaust nozzle well above the nozzle wall pressure at the point of their intersection. For the cases tested, this appears to be between 1.5 and 2.0 times the nozzle wall pressure.

The selected technique of Planar Laser Induced Fluorescence (PLIF) worked well for this investigation. The Nd:YAG laser power proved to be a significant factor in achieving satisfactory results. Our research found that a power per pulse to the test section of 85 millijoules in the UV was satisfactory while a power per pulse of 5 millijoules was not.

References

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- ²Papamoschou, D. and Roshko, A., “The Compressible Turbulent Shear Layer: An Experimental Study,” *Journal of Fluid Mechanics*, Vol. 197, 1998, pp. 453-477.
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- ⁴ ???
- ⁵Thurber, M. C., Grisch, F, Kirby, J. K., Votsmeier. M. and Hanson, R. K., “Measurements and modeling of acetone laser-induced fluorescence with implications for temperature-imaging diagnostics”, *Applied Optics* Vol. 37, No. 21, 20 July 1998, pp. 4963-4978.

a

FIG 5

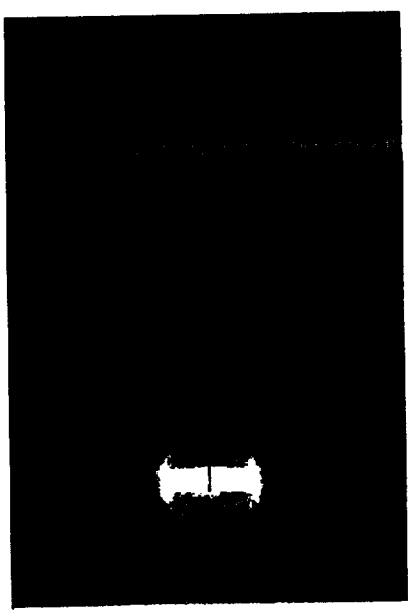


FIG 6

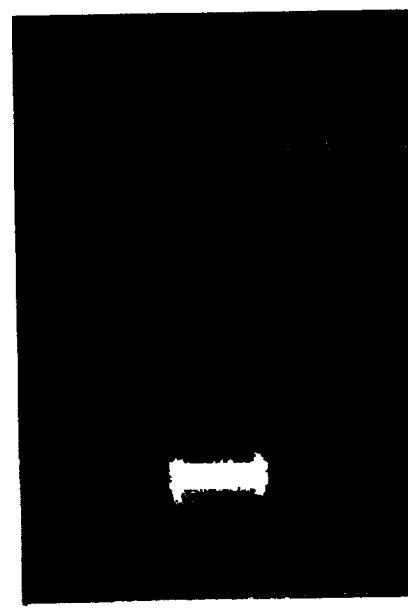
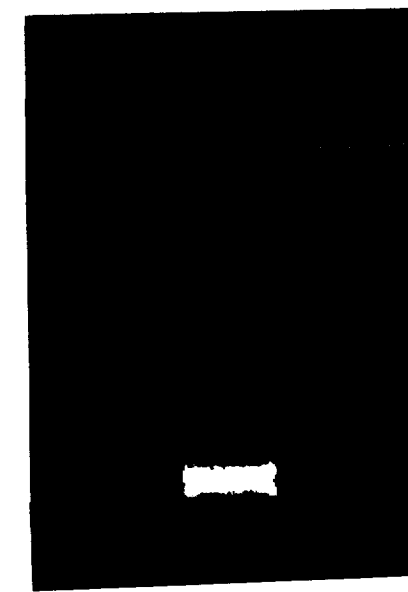
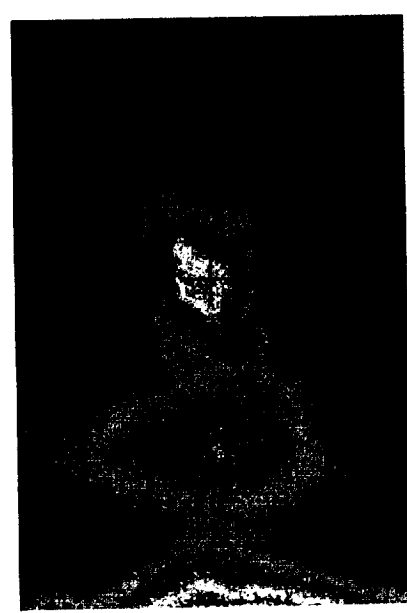
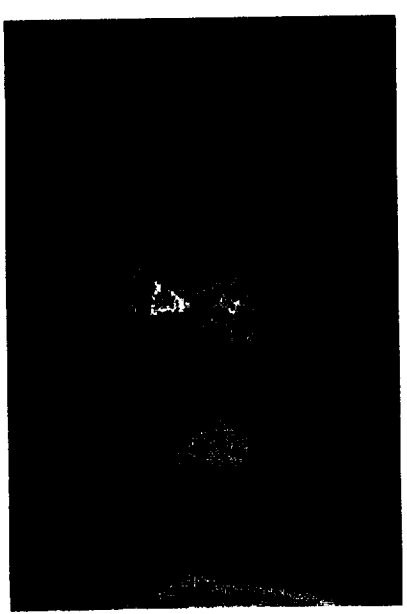
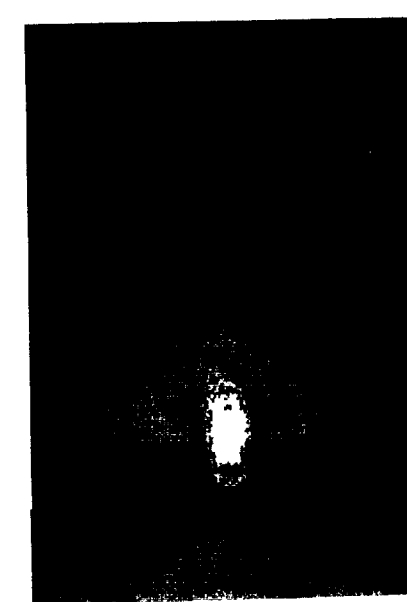
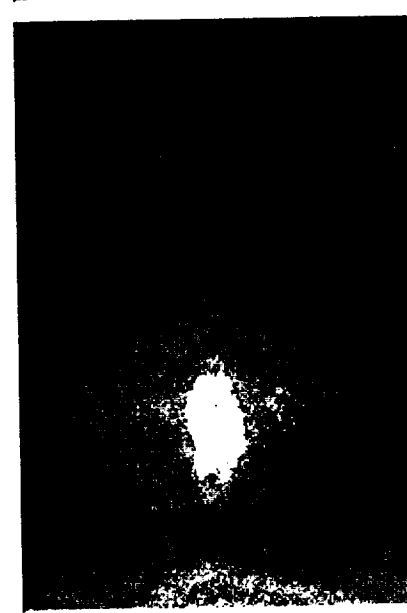
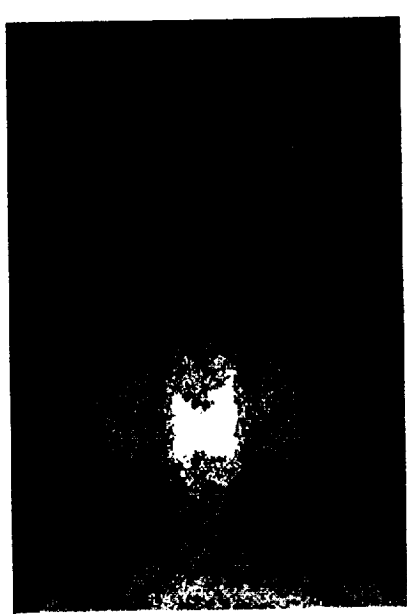


FIG 7



b



C

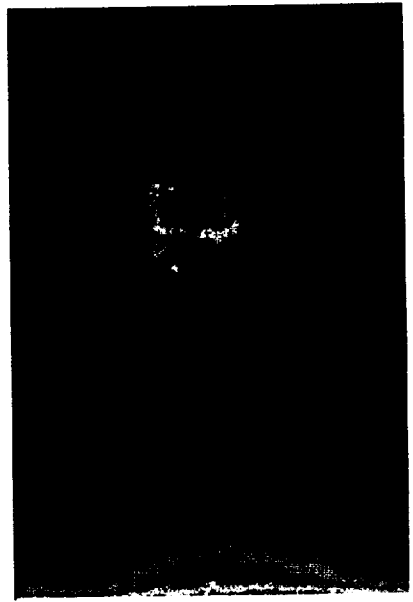
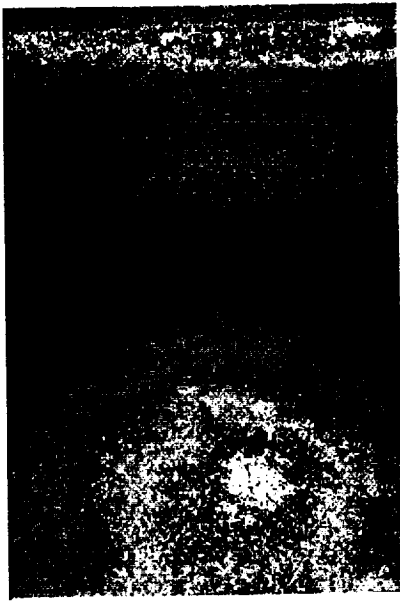


FIG 5

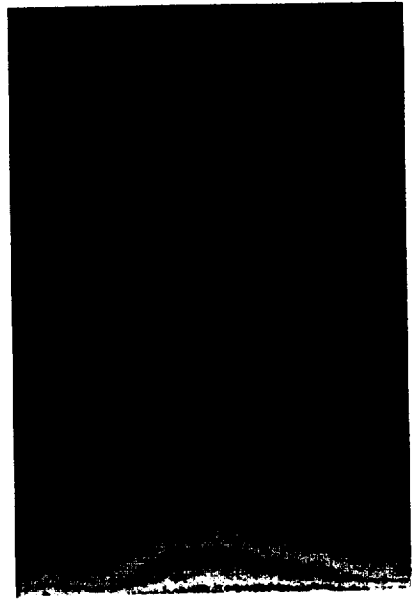
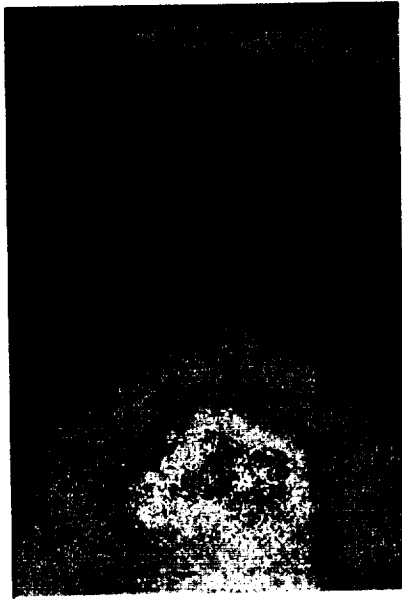


FIG 6

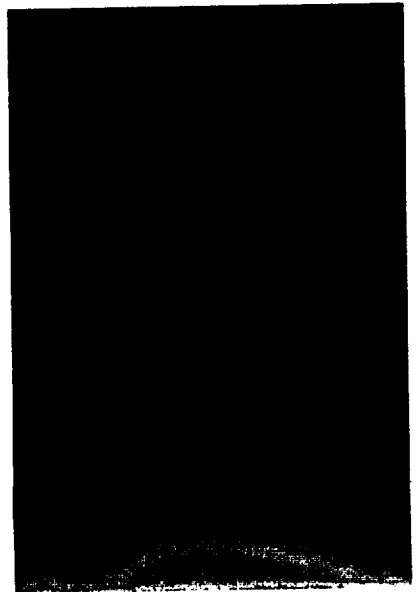
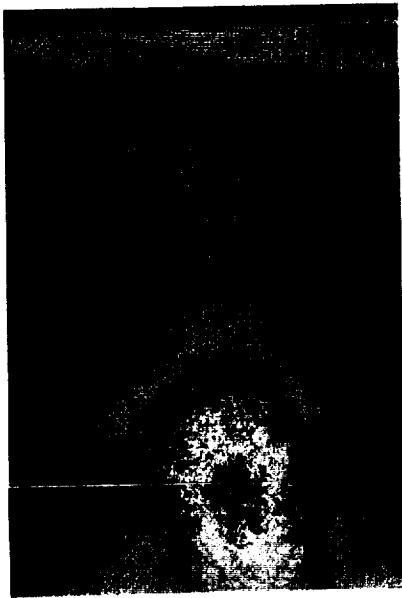
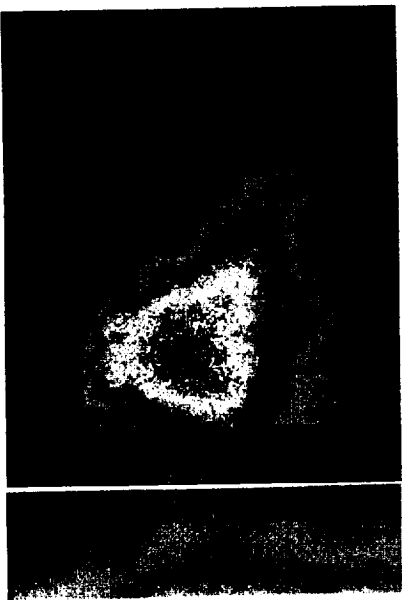


FIG 7