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APPLICATION OF IMAGE PROCESSING TECHNIQUES TO FLUID FLOW DATA ANALYSIS

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Image processing techniques can be useful for analyzing fluid flow data (in this case, calculated values of fluid flow parameters) because of the nature of the data. The results of fluid flow calculations; (a) generate a large number of data points, (b) represent several variables and implicitly contain correlations between some variables, (c) can be usefully represented as two dimensional contours. The technique which has been most useful for representing fluid flow parameters is that of color coding, and that technique will be described here.

Figure 1 shows a conventional aerial photograph of the NASA facility adjacent to Cleveland Hopkins International Airport, the Lewis Research Center. For later reference note the aircraft hangar, the road network, the wind tunnels, cooling towers, and the river flowing around the perimeter of the installation. Figure 2 shows a black and white image reconstructed from a thermal scan of roughly the same scene taken a few hours after sundown. The intensity of thermal radiation is proportional to the temperature of the emitting structure, and in this scan higher temperatures are recorded as lighter (or brighter) shades of gray. Again note the aircraft hangar, the wind tunnels and piping, sheet metal roofed buildings, which are black of colder than the surroundings, having absorbed less heat through the reflective silver paint covering. The roads, parts of the cooling towers, and the river are hotter and appear brighter in the thermal image.

Since the human eye can discriminate only a relatively small number of gray levels, 20 to 30, it is useful to extract more information from a thermal image by color coding the data. Each shade or gray level is assigned a distinct color, and the image constructed. Figure 3 shows the same general area, taken from a somewhat greater altitude, and color coded. The general progression of colors, from cold to hot is black, blue, cyan, green, magneta, red, yellow, and white. The coldest portions of the scene, represented in black, are again easily distinguished, namely the lettering on the hanger roof, the wind tunnels, piping, and sheet metal roofs. The variations in temperature are more apparent in color then in black and white, as shown by the magneta color of the runways, and the magenta, orange, red colors in the river. An underground steam line down the middle of a road is visible, and the heat leak from the open aircraft hangar doors is seen to have easily distinguished contours. The presentation which follows will describe how thermal images are sensed and recorded in digital form, how images are reconstructed from digital data and displayed, and how these techniques are adapted to the display and analysis of compressible fluid flow through aircraft components.

The essentials of recording a digital image are shown in Fig. 4. The line of flight of the aircraft (or satellite in other cases) is from right to left. The instantaneous field of view of the optical system is identified here as a ground resolution element, a rectangular (often square) patch of ground. The data from such a ground resolution element is usually referred to as a pixel, a picture element. The radiation from the ground resolution element is reflected from the rotating scan mirror, through the optics system to a thermal detector. The electronic output of the thermal detector is sent through a sample and hold circuit, whose output is digitized and recorded on magnetic tape. The rotating mirror provides a sequence of GRE's presented to the digitizer, and scans a swath perpendicular to the line of flight. One rotation of the mirror generates a sequence of pixels which are put on magnetic tape as one record. The progression of the aircraft along the line of flight results in the next scan being offset along the line of flight, so that the continuous series of tape records represent a rectangular scene of the ground underneath the aircraft.

Once a scene has been recorded on magnetic tape, the user must recreate an image or series of images from the tape. A schematic of the hardware system used to recreate an image is shown in Fig. 5. In order to quickly preview or screen a scene, a CRT display is necessary. For hard copy, a film recorder or a printer/plotter is required. The system includes a mini-computer with main memory, several removable disk cartridges containing system software and applications programs, magnetic tape units to read and write tapes, and typewriter consoles for user commands. The image output hardware, the film recorder and the CRT display contain limited memory and processor capability and can accept both data and command words from the mini-computer. To create a CRT image the following steps are necessary, as shown on Fig. 6. A record is read from magnetic tape into the mini-computer memory, at a location called the input buffer. As we have seen, this data corresponds to a scan line of pixels from the original scene. The data in the input buffer is reformated and stored along with suitable commands into another mini-computer memory location designated as the output buffer for eventual transfer to the CRT display unit. These activities occur under control of the mini-computer CPU, which finally initiates a transfer of the output buffer contents to the display processor. The net result is that a scan line of up to 512 pixels are stored in the display memory. Repetition of this process can store up to 512 scan lines, usually in a one-to-one correspondence with the records on the magnetic tape. The display memory locations in turn are in an one-to-one correspondence with a square array of locations on the CRT screen, so one can consider the CRT screen image to be made up of 512 x 512 colored dots or pixels. The display processor contains electronics which continuously reads the contents of the display memory and generates a T.V. raster with appropriate red, green, and blue signals for the color CRT (a standard commercial T.V. monitor). The screen is refreshed 30 times per second which is much faster than an image can be read into the entire display memory (about 10-15 seconds).

The color coding for an entire image can be changed much more rapidly then the image because of this method of refreshing the display at 1/30 second intervals. The pixel or data values in the display memory are used as a pointer, or index into a color translation table which contains the red, green, blue information used to generate the T.V. signals. Figure 7 shows a schematic of the color translation table stored in auxiliary read/write memory of the display processor. For 8 bit data ($0\text{-}255_{10}$), 256 different colors can be stored. The unit can store 1024 colors if 10 bit data is to be represented, but in most remote sensing work 24 colors are more than adequate. This scheme restricts the CRT display to 16 gray levels (4 bits) since a gray color requires equal RBG intensity. As stated, the pixel value at each display memory location is used as a pointer to the color information in the color translation table prior to the generation of the T.V. raster.

A color translation table in analogue form is shown in Fig. 8. The gray scale at the top is linear, and contains 16 levels, hence each level represents 16 data values to provide 16x16 = 256 data values. The color scheme contains 12 colors, and again is linear in that the same number of data values are assigned to each color, except for th extreme colors black and white. All data values below a threshold are assigned black and all values above an upper limit are assigned white. The threshold can be chosen to suit the specific data, since the gain of the scan system will vary from scene to scene. This amounts to sliding and stretching a color scheme up, down, and along the maximum data range of 0-255. The next two viewgraphs show an application of color coding for a thermal image. Figure 9 shows another aerial photograph of the Altitude Wind Tunnel of the Lewis Research Center. The points of interest are the wind tunnel, the refrigeration building, the cooling tower, and the water settling tanks adjacent to the cooling tower. Figure 10 shows a color-coded thermal image of the area. The images here represent a refrigerration building associated with a wind tunnel and cooling tower at Lewis. Figure 10(a) at the top was scanned from a higher altitude then Fig. 10(b), so the displayed image was expanded electronically by doubling or quadrupling each pixel, hence the obvious digital nature of the image. The relatively hot water in the settling basins adjacent to the cooling tower is obvious in both pictures, as are the vents on top of the cooling towers.

As shown in Fig. 11, characteristics of the CRT displays to keep in mind are: medium resolution, quick image change, very fast color change, geometric distortion. The geometric distortion results in a square image in memory being displayed as a rectangle wider than high.

The method of forming an image on the film recorder is different in one important aspect, namely the digital data is supplied to a high resolution black and white CRT. The white light emitted from the CRT face is passed through a color filter, then focused on color film. To record a full color image, three separate passes are necessary, one each through a red, blue, and green filter. This requires that for each one pixel image, three "separation" images need to be created, as indicated in Fig. 12. This method creates a very high resolution film image, limited by the deflection capabilities for the electron beam. The film image is formed dot by dot, with the exposure regulated by the amount of time the electron beam is allowed to remain at one place, and hence is highly accurate and reproducible. An example of the quality of image possible with this process is the thermal scan of Fig. 3. The requirements for high resolution and accurate exposure level lead to long times to produce a film negative, of the order of 3-15 minutes, depending on the size of the image.

In Fig. 13 the characteristics of the film recorder image are shown: high resolution, slow image change, slow color scheme change due to sequential color generation, no geometric distortion.

Having discussed the characteristics of the image output hardware, and seen some examples of remote sensing products, we can turn to the discussion of applying these techniques to fluid flow data, resulting from theoretical calculations. The data represent fluid flow parameters such as pressure, temperature, velocity, vorticity as a function of three spatial dimensions or as a function of two spatial dimensions and time. The calculations are implemented by choosing a grid of points (rectangular, square, cylindrical) and assigning boundary conditions and/or initial conditions. Numerical calculations fill in the 3-D spatial grid, or extend a 2-D grid in the time dimension. The final results represent the values of one or more parameters at each grid point, and are often presented as page upon page of tabulated data.

Figure 14 shows a configuration of a curved duct, of square cross section. The elementary 2-D grid is a slice perpendicular to the duct axis. The characteristics of the data are: a large volume of data (but smaller than scenes from remote sensing), a sequence of two-dimensional data arrays, typically 250 stations, low resolution (32x32 or 64x64) at each station.

Any one 2-D slice can be represented as an image by using the grid coordinates of the calculations for the image coordinates, and taking a parameter value such as pressure to be a pixel value. The number of grid points is small so it is usual to interpolate between grid points to obtain a smoothly varying image. The resultant data values are scaled between 0 and 255 to form a data set for an image. The interest in such a configuration is in the three dimensional properties of the flow. One way to grasp these properties is to project the sequence of 2-D slices in a motion picture, and imagine that the viewpoint is that of an observer moving along the flow axis. The movie which will be shown next was generated by displaying calculated values of flow parameters for one frame (at one axial station) on the CRT screen, and photographing the CRT screen with a 16 mm movie camera, driven in single-frame mode by the computer system. Each film clip corresponds to about 250 axial stations. For animation purposes, 4 frames on the film were photographed at each axial station.

The next configuration to be shown is a mixer nozzle for the outlet from a jet engine turbine, Fig. 15. In jet engines, cold air is bypassed around the outside of the combuster, and mixed with the hot combustion products flowing through the engine core. Nozzles at the combuster outlet are arranged in a sinusoidal or wavy fashion to promote mixing of the hot air from the combuster core with the cold air from the bypass. Figure 16 shows the total temperature profile at the final calculation station for a 12 lobe mixer configuration. The temperature scale is shown at the lower right, blue representing colder temperatures, red and yellow representing warmer temperatures. The outline of the mixer nozzles is still apparent showing that the mixing is not complete. The next Fig. 17 shows the same axial station for an 18 lobe mixer. Here the mixing has been more complete as shown by a more uniform temperature across the image. The traces of the 18 nozzles are still visible. The next two figures (18, 19), show the variations of toal pressure through the same configuration. The film clips to be shown next present temperature and pressure parameters for a variety of mixer nozzle configurations.

The movie clips shown present an approach to analyzing or screening large amounts of data. In this system, the flow calculations and grid interpolations were performed on a large computer whose output included magnetic tape containing the data for 256x256 pixel images. To minimize intra-record gaps on the tape, each image was written in only 4 records of about 16 K Byte length each. The tapes were later played on the mini-computer image processor. A run containing 450 axial stations can be displayed on the CRT in about 30 minutes. In order for the research engineer to review and asimilate the data in image form, further data compression is useful, and the 16 mm movie technique was selected. The method of photographing the CRT display with a single-frame motion picutre camera was chosen because it was fast, because the resolution was more than adequate for the data, and because the hardware and film processing capabilities were on hand and available. The computer based system for controlling the CRT and movie camera produced a film clip of 1500 frames in about three hours. At 24 frames per second viewing speed, that film clip runs in just over a minute.

To summarize, these movies have been extremely useful to the research engineers for analyzing data and gaining insight to the fluid flow phenomena under investigation. The usefulness of the technique does not depend on the hardware used, since other systems of hardware/software could be devised. Figure 20 highlights the benefits from this technique, namely to allow assimulation of large amounts of data relating to complex flow phenomena, to use the human eye-brain to integrate and recognize patterns, and the fact that lengthly or complex computer data processing is not required.

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BLACK AND WHITE PHOTOGRAPH

Figure 1. - Aerial photograph of Lewis Research Center.

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Figure 2. - Thermal scan of Lewis Research Center, March 17, 1975 - black-and-white imagery. Altitude, 457 meters (1500 ft); ambient temperature, 5.6^{0} C.

Figure 3. - Color coded thermal scan of Lewis Research Center.

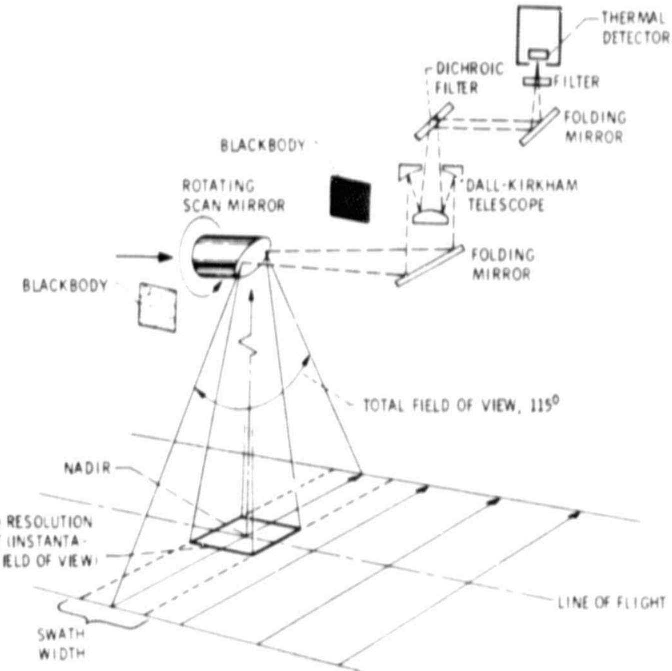

Figure 4. - Schematic of modular multiband scanner (M^2S) system.

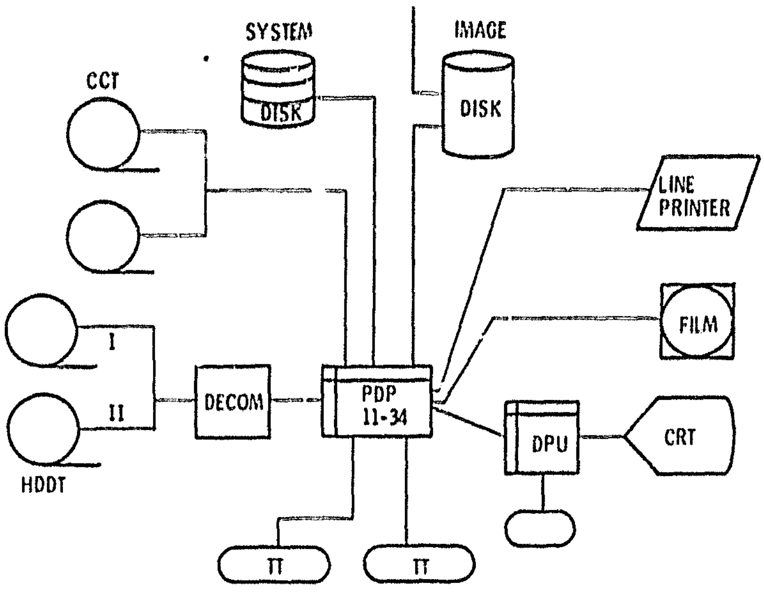

Figure 5. - Image processor system.

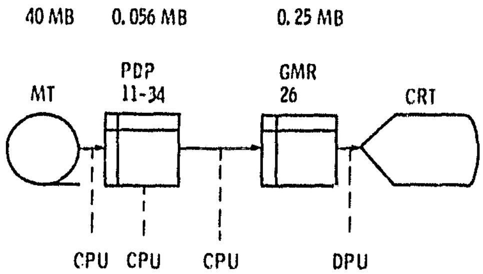

Figure 6. - Reconstruction of digital image on color C.R.T. monitor.

DATA (INDEX)	COLOR B	COLOR G	COLOR R	
0	1010	1010	1010	(GRAY)
1				
2	0000	0000	1111	(RED)
3	0000	1111	0000	(GREEN)
4	1111	0000	0000	(BLUE)
.				
.				
.				
.				
255	1111	1111	1111	(WHITE)

Figure 7. - 12-bit color translation table.

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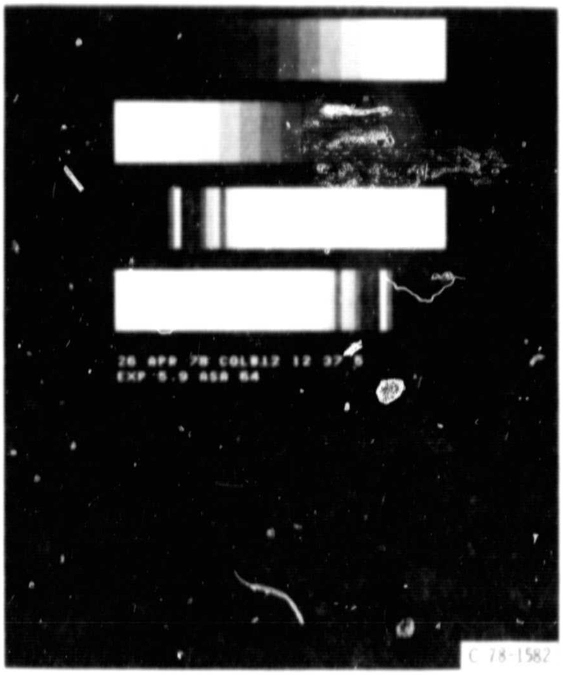
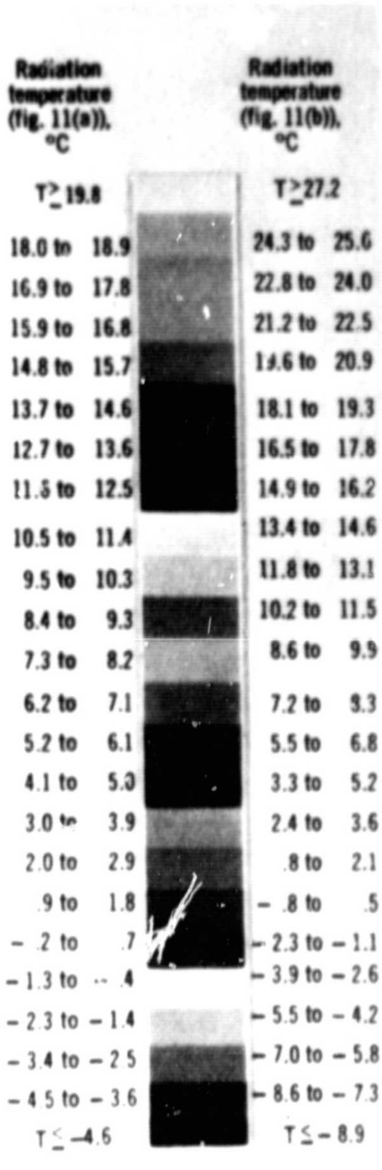
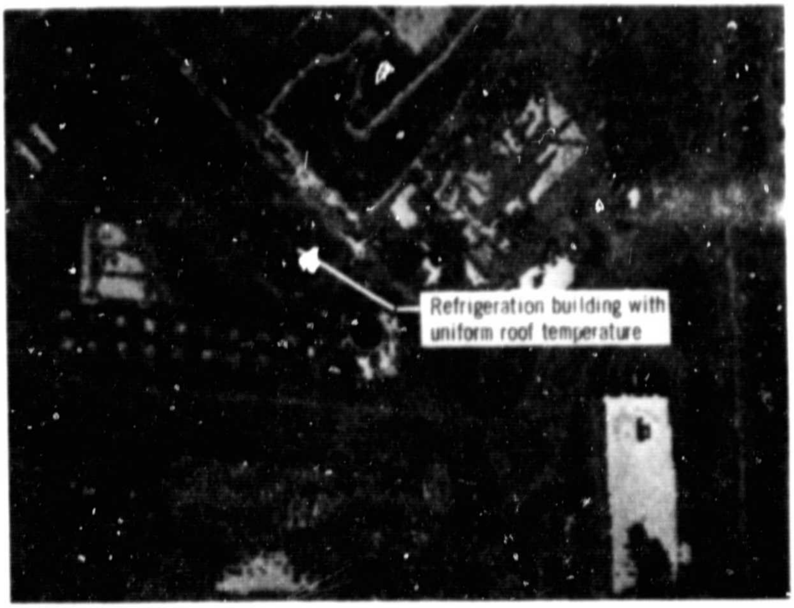


Figure 8. - Grey scale and color translation table.

Figure 9. - Altitude wind tunnel, LeRC.



(a) Refrigeration Building showing high roof temperature from leak in steam line - March 17, 1975. Expanded view from altitude of 457 meters (1500 ft); ambient temperature, 5.6 °C.



(b) Refrigeration Building showing uniform roof temperature after repair of steam leak - April 7, 1976. Altitude, 305 meters (1000 ft); ambient temperature, 3.3 °C.

Figure 10. - Thermal scans of Lewis Research Center Refrigeration Building showing effect of steam leak and repair on roof temperature.

o MEDIUM RESOLUTION	1.25 LINES/MM (SCREEN) 20 LINES/MM (SLIDE)
o FAST IMAGE CHANGE	3 - 10 SECONDS
o VERY FAST COLOR CHANGE	3 - 5 MILLISECONDS
o PARALLEL GENERATION 3 COLORS	
o GEOMETRIC DISTORTION	
o 4 BITS PER COLOR	

Figure 11. - Color T.V. monitor image characteristics.

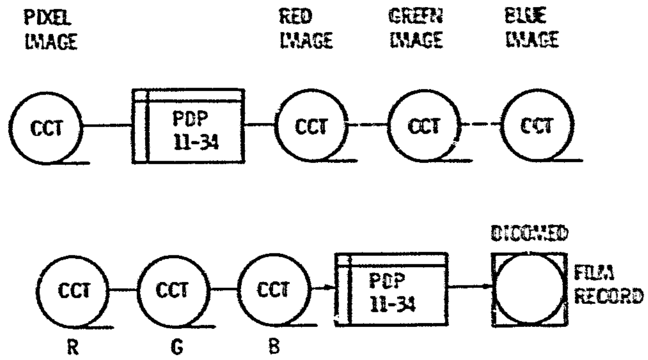


Figure 12. - Reconstruction of digital image on color film recorder.

o VERY HIGH RESOLUTION	50 LINES/MM
o VERY HIGH ACCURACY	
o SLOWER IMAGE, COLOR CHANGE	3 - 15 MINUTES
o SEQUENTIAL GENERATION 3 COLORS	
o 6 - 8 BITS PER COLOR	

Figure 13. - Film recorder image characteristics.

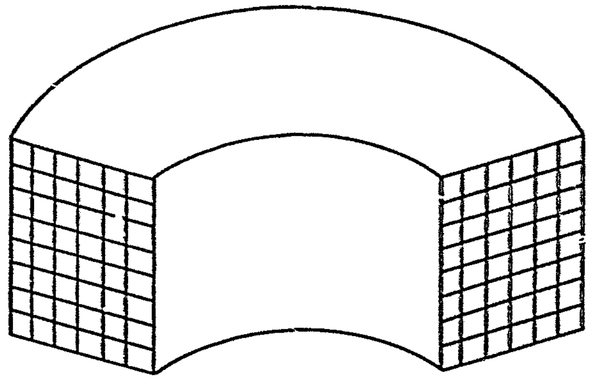


Figure 14. - Flow geometry for square duct with 90° bend.

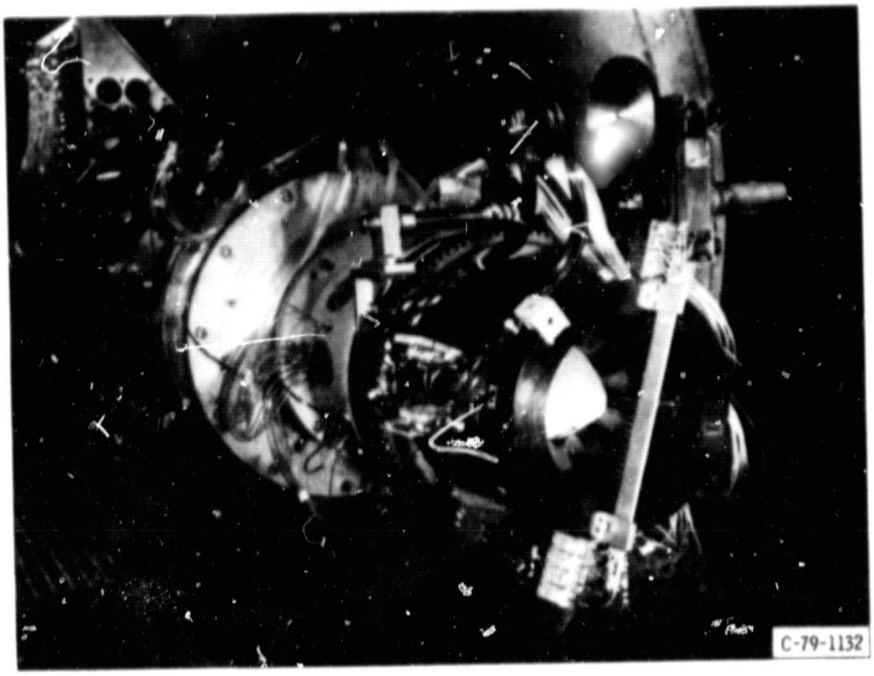


Figure 15. - Jet engine mixer nozzle.

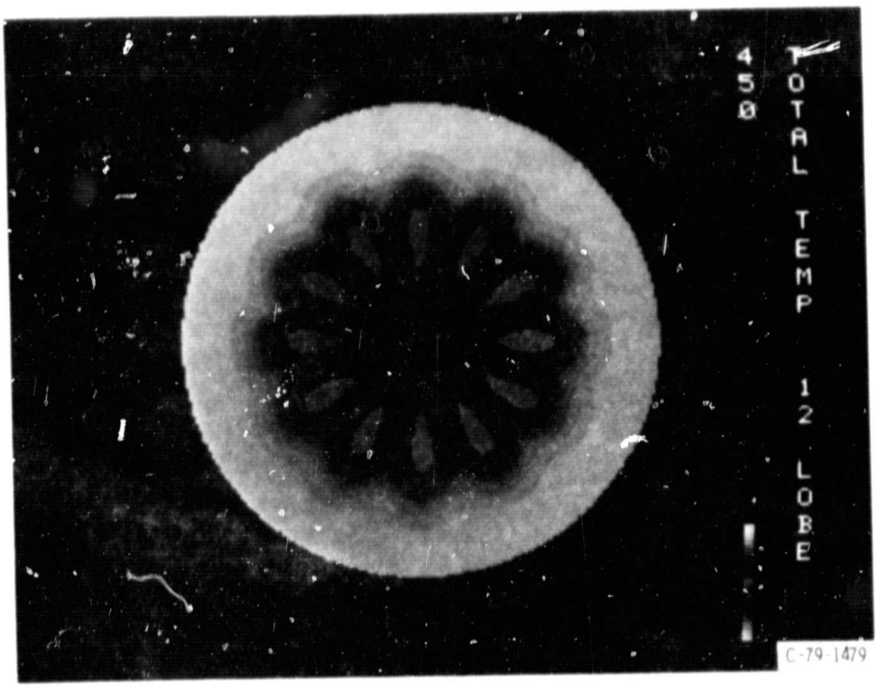


Figure 16. - Total temperature profile, 12 lobe mixer.

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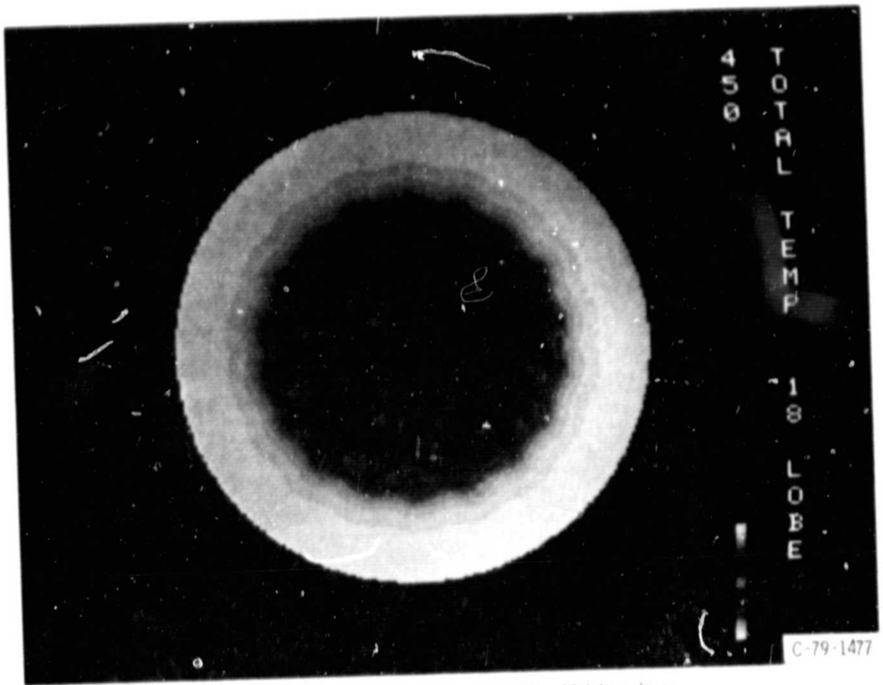

Figure 17. - Total temperature profile, 18 lobe mixer.

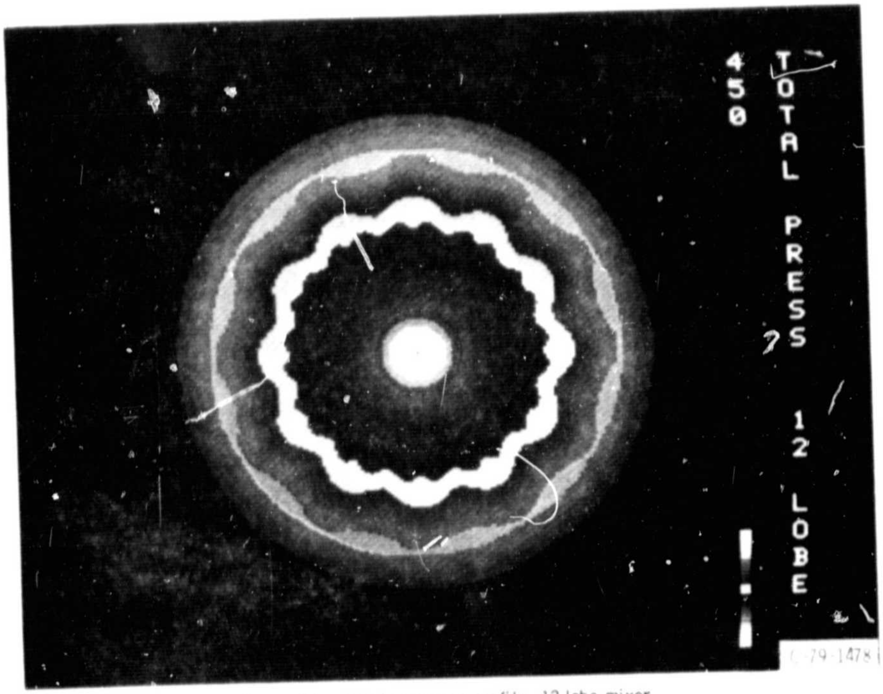

Figure 18. - Total pressure profile, 12 lobe mixer.

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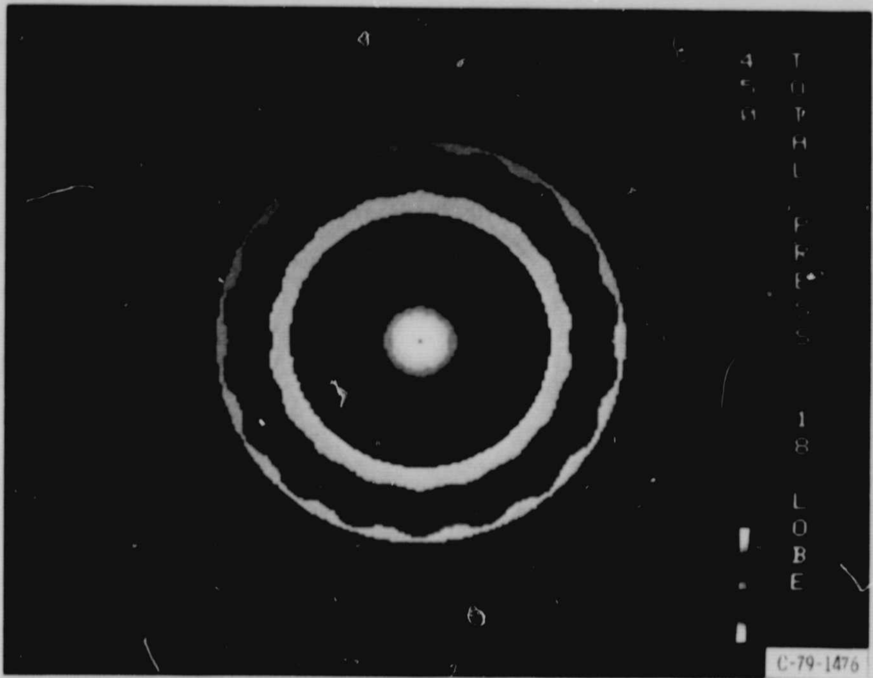

Figure 19. - Total pressure profile, 18 lobe mixer.

- DATA COMPRESSION
- USES EYE-BRAIN TO INTEGRATE AND RECOGNIZE PATTERNS
- SHORTENS COMPLEX COMPUTER PROCESSING
- HELPFUL FOR DEBUGGING CALCULATIONS

Figure 20. - Benefits of graphic display of fluid flow data.