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FLOW TOPOGRAPHY INSTRUMENTATION AND ANALYSIS SYSTEM

TOPICAL REPORT

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ABSTRACT

An instrumentation system has been developed and used to record, display, and analyze two-phase flow topographies. This report describes the devices designed; the computer analysis techniques used to derive two-phase flow distributions, velocities, and interfaces; and the application and demonstration of these techniques during experiments in a model reactor vessel. These techniques have broad instrumentation applicability.

EXECUTIVE SUMMARY

An instrumentation system of hardware and software has been invented and used to record, display, and analyze two-phase flows. This system maps the flow topography, namely the distribution of the phases, the location and velocity of the interfaces separating the phases, and the sizes of distinct entities bounded by such interfaces. In addition to demonstrating the underlying instrumentation system concept, this program has produced specific devices (probes, electronics, and computer interfaces) and analysis tools (computer software) which have guided implementations on other programs. A nearly identical system has been implemented in a 2/15-scale model reactor vessel by the Battelle Columbus Laboratories. Plans are in place to apply similar concepts using somewhat different hardware and software in the Japanese SCTF and the German UPTF as part of the U.S. instrumentation and data analysis contribution to the International 3D program.

In its most elementary form, the concept underlying this instrumentation system combines a large number of simple, rugged sensors with advanced digital computer techniques for data acquisition and analysis. This concept may be implemented in many ways for measurements in numerous fields. In the particular system developed at Creare, sensors which exploit the difference in the conductivities of steam and water are installed at over 300 locations within a vessel; these sensors are neither complicated nor expensive. At every moment the output of each sensor unambiguously indicates the presence or absence of water in its immediate vicinity. At intervals of a few milliseconds, consistent with sensor response, a computer-controlled data acquisition system stores the states of all sensors, thereby recording the phase distribution within the vessel.

The recorded data may be displayed or analyzed. Display techniques include pictorial representation of the phase distribution and interfaces on computer-driven graphics devices or 16mm motion picture film. The films recreate the flow processes at various levels of spatial detail either at their true speed or in slow motion. Computer based analysis techniques have been developed and applied to calculate local and global fluid distribution and void fraction, to determine the location and velocity of interface lines between the phases, to quantify phase entity sizes, and to correlate the two-phase flow topography with other measurements such as pressure fluctuations at various locations. While the demonstration system developed at Creare utilizes conductivity probes to discriminate phases, the display and analysis techniques are general and will work equally well with other types of binary phase sensors, such as optical probes.

The devices and analysis techniques developed during this program have been demonstrated using a model reactor vessel available at Creare. The instrumentation system was used to record a series of countercurrent flow experiments, and the data were displayed and analyzed using some of the developed techniques. This report describes the instrumentation system and the analysis techniques and provides examples of the displays and the results of the data analysis.

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1 INTRODUCTION

Many problems arise within the field of experimental fluid dynamics which call for methods for recording, displaying, and analyzing the details of rapid and complex two-phase flow processes. For example, the specific problem which led to the work reported here is that of a postulated broken cold leg pipe leading to a Loss of Coolant Accident (LOCA) in a Pressurized Water Reactor (PWR). During calculation of such an event, steam generated in the reactor core flows up the annular downcomer between the core barrel and the pressure vessel on its way to the break. At the same time Emergency Core Coolant (ECC), which is being injected into the cold legs, attempts to fall through the downcomer to the lower plenum. If the upward steam flow rate is high enough, some or all of the ECC water may be driven out the break, delaying core reflood. Detailed data describing two-phase flow patterns, velocities and entity sizes are of value to those developing and assessing computer codes for LOCA calculations.

In the past the experimental techniques available for obtaining detailed quantitative information about transient two-phase flow processes of this kind have been quite limited. Countercurrent flow in the context of reactor vessel refill has been studied by recording lower plenum water level as a function of time in scale models under various conditions. [1,2,3] Such measurements provide no information about the flow regimes and patterns occurring in the annulus, except to show that the rate of fluid delivery to the lower plenum can vary greatly even under steady-state test conditions. Glass vessels and high-speed cameras have been used to obtain direct views of countercurrent flow topographies, but this method too is of limited utility. Glass can be used only in simple geometries at relatively low pressure and alters some effects such as wall heat transfer. In addition, the information obtained is non-numerical and not amenable to quantitative computer analysis for straightforward comparison with codes.

Sophisticated instrumentation can be used to obtain transient quantitative measurements of local density, velocity or other variables in two-phase flows [4]. While these techniques have demonstrated value, there can be significant uncertainties in data interpretation and flow interference [5]. Moreover, some devices (e.g., gamma densitometers) can be prohibitively expensive and complex to operate reliably unless they are restricted to a small number of locations. They are not suitable for detailed mapping of multi-dimensional flow fields. A significant motivation for the present work, therefore, was the recognized value of a simple, rugged, and compact sensor that could be installed in numerous locations throughout a flow field to provide phase distribution or velocity data to complement pressure and thermocouple data.

Creare Incorporated has developed for the Nuclear Regulatory Commission a unique flow topography instrumentation and display system. This system of hardware and software provides a new and versatile method for recording and then displaying in a convenient pictorial format the details of complex and rapidly changing two-phase flow patterns. It utilizes simple and reliable binary (liquid/vapor) phase sensors mounted at a large number of points to determine the overall fluid distribution, and uses a computer to sample the sensor states at very high rates. All data are recorded in numerical form and are therefore readily amenable to computer sorting, editing, and analysis. For example, routines have been developed which automatically compute the position and velocity of steam/water interfaces.

The first version of this system was invented and demonstrated by Creare late in 1977 and reported in April of 1978 [6]. It was first demonstrated in a 1/15-scale model reactor vessel at Creare, but the method is readily adapted to other scales, geometries, and applications. Since its development, the flow topography instrumentation system has been implemented in the 2/15-scale vessel at Battelle Columbus Laboratories. Plans are being made to employ similar systems in the Japanese Slab Core Test Facility (SCFT) and the German Upper Plenum Test Facility (UPTF) as part of the U.S. instrumentation contribution to the international 3D reactor safety program.

The next section of this report provides a general summary of the principles, components, and capabilities of the Flow Topography system. The following sections provide specific details. Section 2 describes the test facility that has been used to develop and demonstrate the system, including the vessel, its instrumentation, and the computer interface. Section 3 describes data display and editing techniques, and Section 4 discusses analysis techniques. Appendices discuss sensor performance and summarize the countercurrent flow tests performed.

1.1 System Overview

The Flow Topography system relies on the fact that under many conditions the electrical resistances of the liquid and vapor phases of water differ radically. Without actually measuring these resistances, conductivity sensors inserted in a region of two-phase flow can clearly indicate at each moment whether or not the immediate vicinity of the probe is occupied by liquid. A large number of these sensors can be installed throughout a volume of interest and connected to a computer-controlled data acquisition system. The complete set of binary states (liquid or vapor) of the array of sensors at a particular instant provides a "snapshot" of the two-phase topography existing within the vessel at that time. The snapshot, or data frame, is recorded in a (binary) numerical form. It can be used to recreate a visual representation of the flow process on a graphics device, or it can be subjected to computer analysis to extract other information.

Figure 1 shows a sequence of computer-generated images representing data frames (snapshots) recorded in a model vessel which is described in Section 2.2 and in Reference 6. The larger rectangle in each frame represents the cylindrical downcomer annulus. For clarity, it is shown sliced vertically and rolled out flat; the horizontal dimension is therefore its circumference. (Details such as the cold leg locations have been deleted for simplicity.) Two hundred eighty-eight sensors were mounted in the annulus in a 12x8x3 array. In each image the sensors that were indicating the liquid phase at the moment the frame was recorded are represented by small symbols at the appropriate positions. Blank areas were filled with steam. The narrow rectangle to the left represents a vertical stalk of sensors mounted in the lower plenum of the vessel, which is physically below the annulus. Additional sensors were mounted in the vessel's simulated broken leg; whenever these sensors indicate significant amounts of water being bypassed, a small triangle appears just above the annulus.

The data frames shown in this figure were recorded at approximately 1 second intervals and span an entire countercurrent flow test. Steam flows generally upward and water attempts to fall through the downcomer to fill the lower plenum. Frames were recorded at the rate of 108 per second, so only a small fraction of the data are shown. Water being injected through cold legs near the top of the annulus is first observed in the third frame. During the next three seconds the fluid moves downward until it nearly fills the annulus. Following that, the annulus again becomes

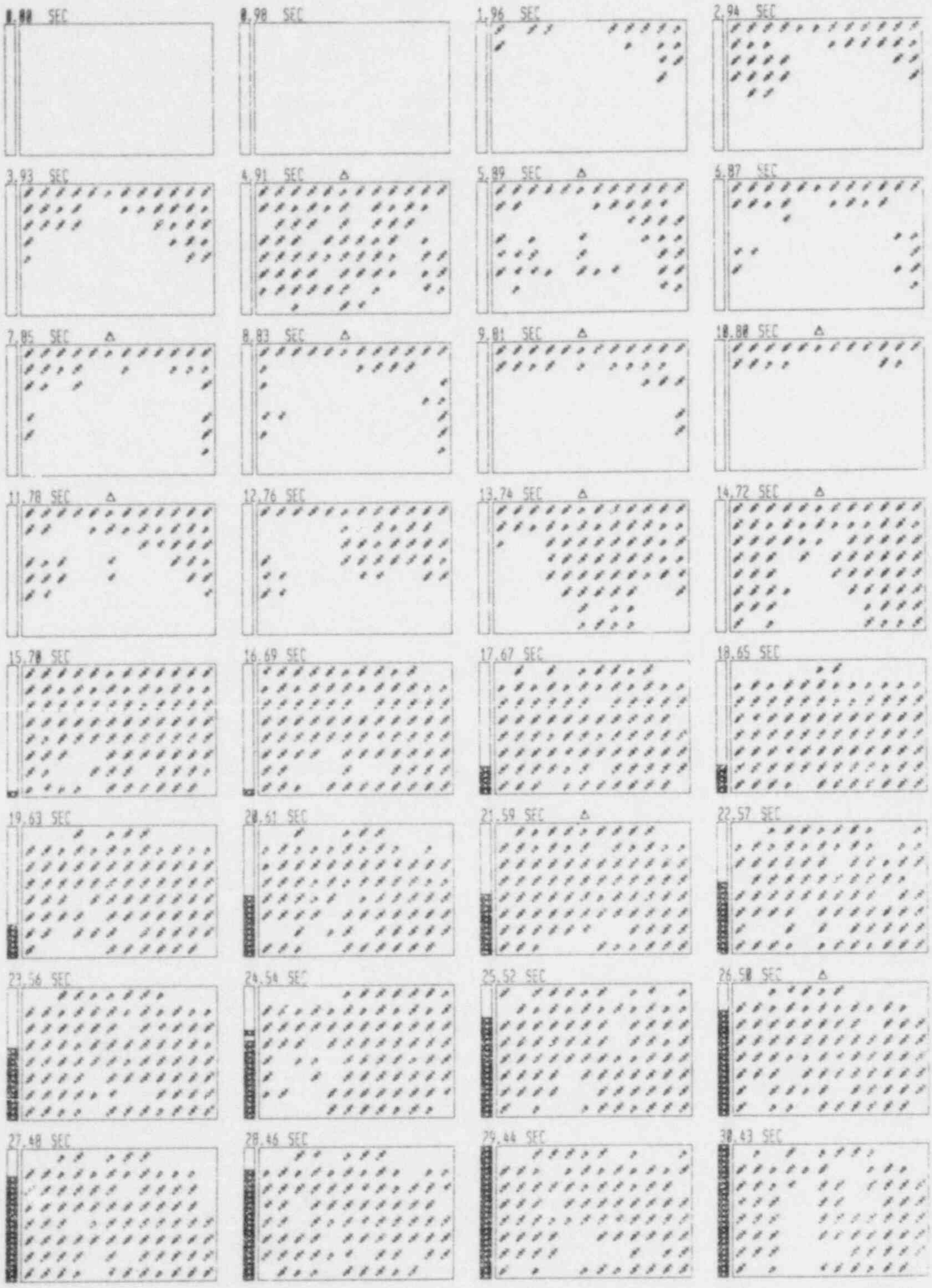


Figure 1. SEQUENCE OF DATA IMAGES SHOWING LOWER PLENUM WATER LEVEL AND DOWNCOMER PHASE DISTRIBUTION

nearly empty. Since no water appears in the lower plenum and since the sensors in the broken leg remain on almost continuously, it is clear that the water that had filled the downcomer was forced up and out the broken leg while newly injected water was being directly bypassed. During the remainder of the sequence the annulus again fills with water, and delivered water eventually fills the lower plenum. Since this test was conducted with water and steam supplied to the vessel at steady rates, the observed alternation between filling and bypass was a result of physical processes such as flooding, heat transfer and condensation in the downcomer.

Data frame images can be displayed on a video terminal, as well as in hard-copy form, either in real time or after the conclusion of a test. If a video display of a sequence of images is synchronized with the operation of a camera, the images can be transferred to successive frames of a movie film. When projected, the film recreates the motion of the recorded flow process. The process can be viewed at its true speed or in controlled slow motion. A sample film produced from data recorded during a series of countercurrent flow tests is available.

The data used to generate the topography images are stored in numerical form and can therefore be subjected to computer-based analysis. In this report we describe several analysis methods that have been developed and implemented, including image enhancements, approximations to liquid and void fractions, digital filtering of recorded and computed quantities, automatic calculation of phase interface position and velocity, and correlation of interface motions with vessel pressure variations. These are presented as examples of basic analysis techniques; many others could be developed as required for specific applications.

For example, Figure 2 shows a sequence of data frames which have been processed by a computer routine which automatically locates a single boundary to partition the annulus into steam-filled and liquid-filled regions. In this figure, the lower plenum display has beem omitted and each set of three sensors ranged across the annulus gap is represented by a single symbol. These frames, taken from an early portion of the test shown in Figure 1, were recorded at 0.05 second intervals during the initial advance of fluid down the annulus. The algorithm chooses an interface location systematically; small regions of the opposite phase, which in this context are principally random, are permitted to exist within the main partitions. Though similar operations can be performed easily by a human being, the very large number of data frames recorded during even one test makes it impractical to do so for any significant amount of data, and the computer algorithm more reliably adheres to a consistent interface definition. The routine which generated the interface lines shown in this figure processes and displays about 10 data frames per second. The computed interface lines, or any other analytic display, can also be included in the films generated from recorded data.

Figure 2. DOWNCOMER TOPOGRAPHY IMAGES WITH SINGLE COMPUTER-DEFINED PHASE INTERFACE

2 DEMONSTRATION TEST FACILITY

The use of large arrays of sensors to record two-phase topographies under highly dynamic conditions is a new experimental technique which promises to be of value in a wide variety of fluid dynamics applications. In order to develop and demonstrate the capabilities of the method, a model system has been installed and used in a representative application: a scale model of a PWR vessel. This system has been used to perform a series of countercurrent flow tests which simulate one portion of a postulated loss-of-coolant accident. The rapid and complex flow dynamics which occur during these tests provide a good test of the topography recording system, and the data obtained contribute to an improved understanding of the governing phenomena.

2.1 Phase Sensors

A binary phase discriminator which exploits the differing conductivities of steam and water is nothing more than an electrical circuit with a small physical gap in it. The gap is positioned at a point of interest, and a voltage is applied to the circuit; the amount of current which flows is a function of the electrical conductivity of the medium bridging the gap. Because the conductivities of steam and water differ radically under most conditions, such a sensor can clearly indicate which phase occupies the gap. We emphasize that in our system the probes are used only to determine whether water or steam is near the sensor; the probes need not measure the conductivity of either phase.

The circuit used in the probes is a simple bridge. A constant voltage V_i is applied through a discriminating resistor to one side of the sensor gap, and the other side is connected to ground. Depending on the conductivity of the medium bridging the gap, the voltage V_o observed at the upper end of the gap varies between 0 and V_i. Since the conductivities of steam and water normally differ by 2 to 3 orders of magnitude, it is not difficult to choose an intermediate value for the resistor so that V_o will usually be near one of the extremes. The high value, near V_i, indicates the presence of steam or air, and the low value, near zero, indicates water. The discrimination is effected by a semiconductor chip. Values of V_o in the lower third and upper third of the possible range produce low and high states respectively; values in the center of the range produce an unpredictable (but definite) state.

Conductivity sensors can be implemented in a variety of ways to meet the needs of specific applications. The geometry of the probes and the choice of materials used to form the sensor electrodes and their insulators affect the speed of probe response to wetting and unwetting and the expected lifetime of reliable probe operation. We describe here the particular design which proved to be suitable for our demonstration tests. Certain details may require modification for other applications, and we identify those which must be given careful attention.

Our tests of the flow topography system used a model vessel containing steam and water near atmospheric pressure. Probes of the type shown in Figure 3 are inserted into the downcomer annulus through pressure seal fittings threaded into the outer vessel wall. The body of the probe, which serves as the negative electrode and is grounded to the body of the vessel, is 0.187 in. OD stainless steel tubing. The tubing is drilled through one side at three places with 0.025 in. holes. Teflon round stock, drilled through to form cylindrical buttons, is pressed into these holes. Thirty gage insulated wire is threaded through the Teflon buttons and out the far end of the tube. The sensor electrodes are short sections of 0.062 in. diameter stainless steel rod, soldered to the wire and pressed into the

Teflon buttons. A silicone potting compound is injected into the tubing to provide insulation between the three sensors and the probe body and to provide a pressure seal.

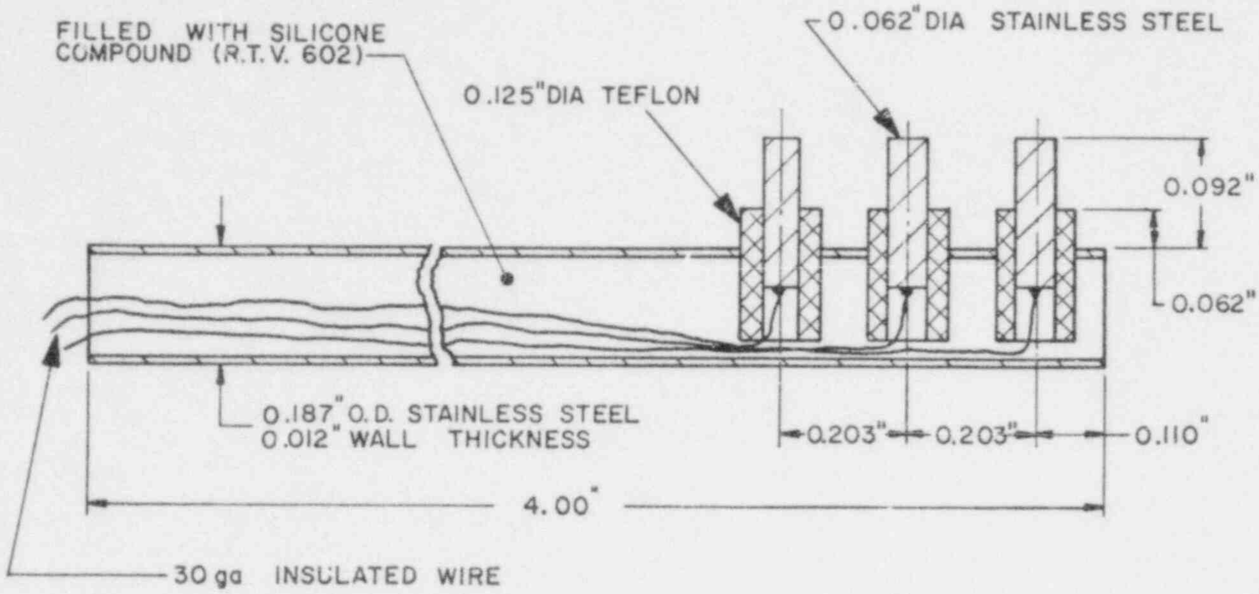


Figure 3. PHASE DISCRIMINATION PROBE USED IN DEMONSTRATION VESSEL

For the range of temperatures encountered in our testing, Teflon is an ideal material for the exposed insulator; water will not adhere to it, so the response of the probe to unwetting is very fast (about 1 millisecond--see Appendix A). The probes are mounted so that the sensor electrodes extend horizontally from the probe body to minimize the chance of pools or droplets forming on their tips. Since leakage to the probe interior could produce an electrical short-circuit, a good seal between the electrodes, their surrounding buttons, and the probe body is required. The potting compound which fills the tube must initially have a low viscosity and be injected in a way that leaves no air spaces. After setting, it must maintain a good seal (without expanding) through a large number of thermal cycles. For the range of conditions encountered in our tests, Type 602 RTV compound satisfied these requirements.

Other investigators have noted that the performance of conductivity probes can be degraded by electrochemical effects [7,8]. As current flows through a sensor, its electrodes may be dissolved, their surfaces may become electroplated with minerals dissolved in the water, or they may become electrically polarized. Such effects can reduce the inherent conductivity of the sensors, causing them to show the high voltage typical of a steam environment even when completely submerged. Early verions of the probes used in this program did exhibit limited lifetimes due to corrosion and polarization; these problems have been eliminated in the present design. The choice of electrode materials and surface area and the duty cycle of the powering electronics are the most important variables. Three hundred sensors have been used to perform several dozens of tests with no failures, and lifetime tests have been performed which indicate that these sensors will operate reliably for several thousand hours while submerged and powered (Appendix A).

2.2 Vessel Instrumentation

An array of these probes was installed in a 1/15-scale PWR model. This vessel has an inner diameter of 12 in., a downcomer length of 24 in., and an annulus gap of 0.625 in. Its lower plenum holds 13.7 gal. (see figure and more detailed description in Reference 6). In order to perform countercurrent flow tests simulated reverse core steam is injected through the center of the core barrel while ECC water is injected through three cold leg inlets near the top of the annulus. The water and steam can be injected at variable rates which were limited to 90 gpm and 1 lbm/sec respectively in our tests.

In order to record annulus flow topographies in this vessel, 96 conductivity probes were installed at regularly spaced points throughout the downcomer. Twelve vertical columns containing eight probes each are spaced evenly around the circumference of the vessel. Since each probe includes three sensors, there are altogether 288 independent sensors in the annulus. The center-to-center distance between probes is 3 in. in the horizontal direction and 2.5 in. vertically, except for the top row which sits above the injection legs and is 5.5 in. above the second row of probes. The center sensor of each probe is near the center of the gap, while the two outer sensors on each probe are near the vessel and core barrel walls. Since the probes block only 6.5% of the annulus cross-sectional area, their interference with the flow is minimal. As described in the next section, the binary states of all sensors are recorded simultaneously, normally 108 times per second. Each of these recorded data frames provides an instantaneous snapshot of the distribution of fluid and steam in the annulus with a resolution determined by the inter-sensor spacing.

To augment the information provided by the annulus sensor array, the following additional instrumentation has been installed:

1) A vertical stalk of 24 conductivity sensors is mounted in the lower plenum.

2) A pair of conductivity sensors is mounted in the simulated broken leg.

3) Four pressure transducers are used to measure gage and differential pressures.

4) An orifice meter is used to measure the supply rate of simulated core steam.

5) The ECC water supply rate is indicated by a magnetic rotameter. A thermometer in the supply tank measures the water temperature.

Conductivity sensors in the lower plenum and broken leg are sampled along with those in the annulus, as binary on/off states 108 times per second. The sensors in the lower plenum measure the volume of water delivered there; the 24 sensors are spaced approximately 1 in. apart with the lowest sensor at the 1.2 gal. level and the highest at 10.7 gal. Two separate probes, each containing one conductivity sensor, are mounted in the broken leg about 6 in. from the annulus to indicate the presence of fluid being bypassed. The sensor gap which must be bridged to complete their circuits is about 1 in. rather than 1/16 in. as in the annulus sensors, so they are activated only by a substantial mass of fluid passing through the broken leg.

A Tyco Model AB 200 psig pressure transducer is used to measure lower plenum gage pressure. Three Celesco Model P3D ±25 psid transducers measure pressure differences between three pairs of points. One side of each transducer is connected to a tap located at the top of the annulus near the broken leg. The opposite sides of the transducers are connected to taps at:

1) the top of the annulus on the opposite side of the vessel,

2) the bottom of the lower plenum directly below the broken leg, and

3) a point external to the vessel (measures ambient pressure).

The output of an orifice meter consisting of a Rosemount Model 1151 differential pressure transducer connected across an ASME standard flow metering orifice is used to compute the mass flow of simulated core steam. Outputs from the five pressure transducers are digitized by a 12-bit A/D converter and sampled by the computer, nominally at a rate of 50 times per second for each instrument. The ECC water supply rate and temperature, which are constant during each test, are recorded by hand.

2.3 Computer Interface

The output from each conductivity sensor is a voltage V_o which varies between zero and V_i the bridge input voltage. It is usually near one of the extremes and thus defines a binary state indicating which phase, liquid or vapor, is present at the site of the sensor. A digital latching circuit is used to sample the state of a sensor at a particular moment and hold it for subsequent transfer to a computer or other recording device. One latch is provided for each sensor so that a single strobe pulse can simultaneously record the states of all sensors. Sensor states are recorded as unambiguous binary digits which require no further conditioning or interpretation. Because the latching operation occupies only a few microseconds, the input voltage V_i is applied to the sensor only for a brief period at each sample time. By operating sensor power with a duty cycle of 1%, electrode degradation due to electrochemical processes is minimized. The electronic circuitry required to operate the sensor array is simple, compact, and inexpensive, so it is practical to build systems containing many hundreds of sensors. The demonstration system in use at Creare handles up to 640 sensors and provides sampling rates of up to 432 complete data frames per second.

Creare operates a large minicomputer (a Digital Equipment Corporation PDP-11/70) to support laboratory data acquisition and analysis. This machine runs under a multi-user operating system and is able to record high-speed input data from several concurrent experiments. The flow topography electronics and applicable portions of the computer system are shown in Figure 4. The flow topography experiment is typically only one of several activities being controlled and does not in itself require the support of a large computer. Dedicated recording and display systems using much smaller computers have also been built without loss of performance. The test vessel is fitted with a total of 314 conductivity sensors; one frame of probe data is formed by simultaneously latching the states of all sensors. Scanning electronics extract these data bits in groups of 10, attach a 6-bit channel address to form a 16-bit computer word, and transfer the word to the computer via interface hardware. Thirty-two successive transfers copy the full data frame, and the process is then repeated, normally at a rate of 108 frames per second. At the same time, analog signals from the pressure transducers are digitized and moved to computer memory, nominally at a rate of 50 values per second for each channel. All data are accumulated in memory buffers and copied to disk files in real time. From there they can be copied to magnetic tape for permanent storage or transfer to other facilites.

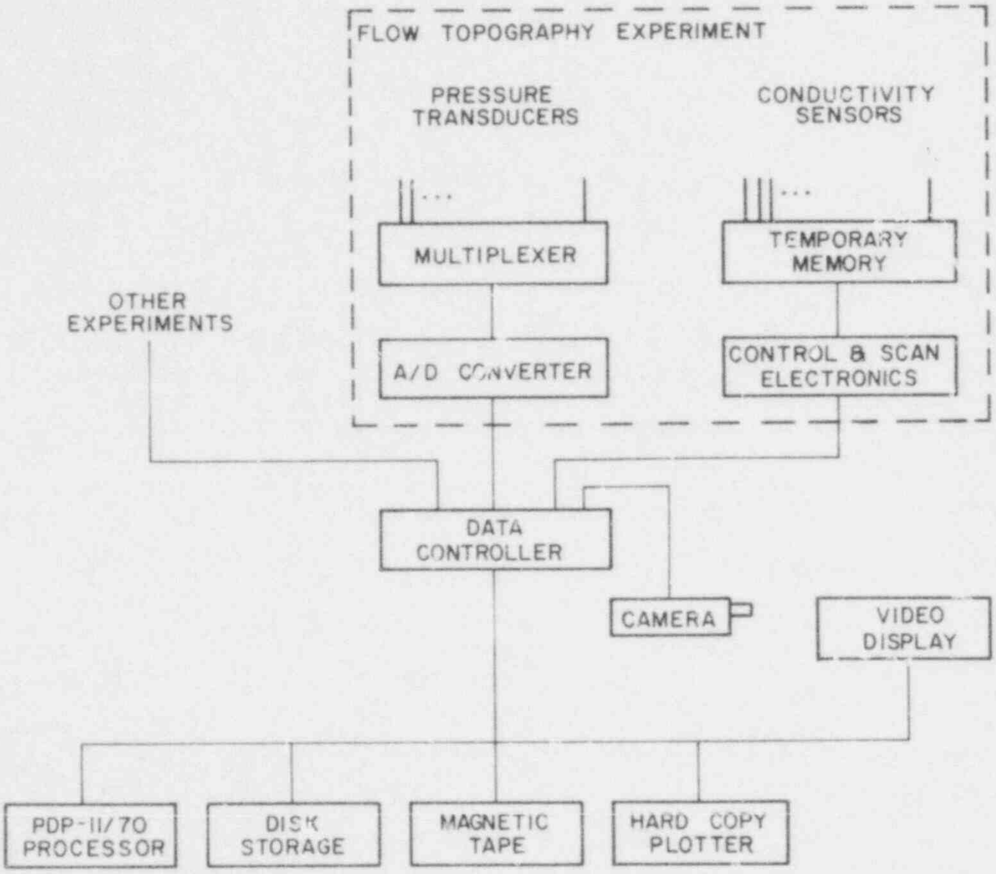


Figure 4. DATA ACQUISITION AND PROCESSING SYSTEM

2.4 Recording Countercurrent Flow Tests

The test facility has been arranged so that tests can easily be performed by a single operator. Valves controlling steam and water are mounted near the vessel and a computer terminal is stationed nearby. The code responsible for recording test data is controlled from the terminal. While the test is in progress, all digital and analog data frames are written into disk files. At the same time a subset of the digital data frames (1 to 3 per second) are retrieved from the disk and displayed on the video terminal. The operator monitors this display to guarantee that the test is proceeding correctly and that the data are reaching the computer file. At the conclusion of the test some post-processing is required to put the data files in their final forms. The time required to perform a countercurrent flow test is typically about five minutes, with another five to ten minutes being required for data file post-processing.

Once a test has been completed, the recorded data are available in three files: a short test descriptor file containing fixed parameters, a digital data file containing conductivity probe data, and an "analog" data file which contains digitized output from the pressure transducers. The digital file is checked for consistency and compressed by removing redundant channel labeling information. The test descriptor file is then updated by adding values computed from the contents of the digital and analog files; these include the average lower plenum pressure and the mean rate of delivery of water to the lower plenum. These values, used with others already available, permit calculation of the dimensionless steam flow rate J^*_{gc} and the dimensionless rate of water delivery to the lower plenum J^*_{fd}. These parameters are described in previous reports of countercurrent flow data analysis [9,10]

3 DATA DISPLAYS

After completion of a test the recorded conductivity probe data frames can be recalled and displayed in the form of pictorial representations of the fluid distribution within the vessel. Individual data frames can be displayed on hard copy or video plotters, and movie films can be produced which show all or part of a test at its true speed or in controlled slow motion. Techniques have been developed to enhance the clarity of the data by suppressing its random elements. Recorded gage and differential pressure histories can be displayed as functions of time.

3.1 Topography Snapshots

A single frame of conductivity probe data records the distribution of the liquid and vapor phases within the vessel at a particular moment, and its content can be displayed in a pictorial form. In order to obtain a clear view of the annulus of the model PWR downcomer, it is convenient to show it "unrolled". Figure 5a is a computer-generated example of this format. The annulus has been sliced vertically at a point opposite the broken leg and rolled out flat. Its height and "width" (circumference) are drawn to scale, but the third dimension (across the annulus gap) is exaggerated for clarity. The circles marked "C" are cold leg inlets in the outer (front) wall, and those marked "H" are model hot legs passing through the annulus. A circle marked "B" is at the location of the simulated broken leg; it contains two triangular symbols representing the conductivity sensors mounted there. Each of the 96 conductivity probes in the annulus is represented by a triplet of symbols corresponding to its three sensors. The + signs represent sensors near the vessel (outer) wall, the o's are the sensors at the center of the gap, and the x's the sensors near the core barrel wall. The vertical column of sensors in the lower plenum is represented schematically by the column on the left. Figure 5b shows an actual data frame recorded during a countercurrent flow test. Only those sensors activated by the presence of water are shown, so the blank areas were filled with steam.

A sequence of images can be juxtaposed to show changes in the flow pattern over long or short intervals. The example shown in Figure 1 was discussed in Section 1.1; a simplified format is used there to allow more frames to be printed on one page. Some of the outlines are omitted, and a single triangle is printed just above the annulus for every frame which had either of the broken leg sensors activated. Figure 6 gives a more detailed view of a portion of a test with higher steam flow, frames being shown at 0.1 second intervals. (These frames are from test ST801E--see Appendix B.) The format has been further simplified by omitting the lower plenum and by representing each annulus probe with a single symbol. During the period spanned by this sequence of data frames a fluid mass in the upper annulus expands and contracts several times. No fluid was delivered to the lower plenum during this time, and bypass to the broken leg was nearly continuous.

The figures shown here were drawn by an electrostatic plotter which produces one page of output in about five seconds. It is also frequently useful to generate topography snapshots on a video terminal, which can produce a similar figure in a much shorter time. Video displays are useful for real-time monitoring of live data, for interactive data study and analysis, and for transferring data to film.

POOR ORIGINAL

a) All sensors shown

b) Typical data frame

Figure 5. SAMPLE DATA DISPLAY FORMAT

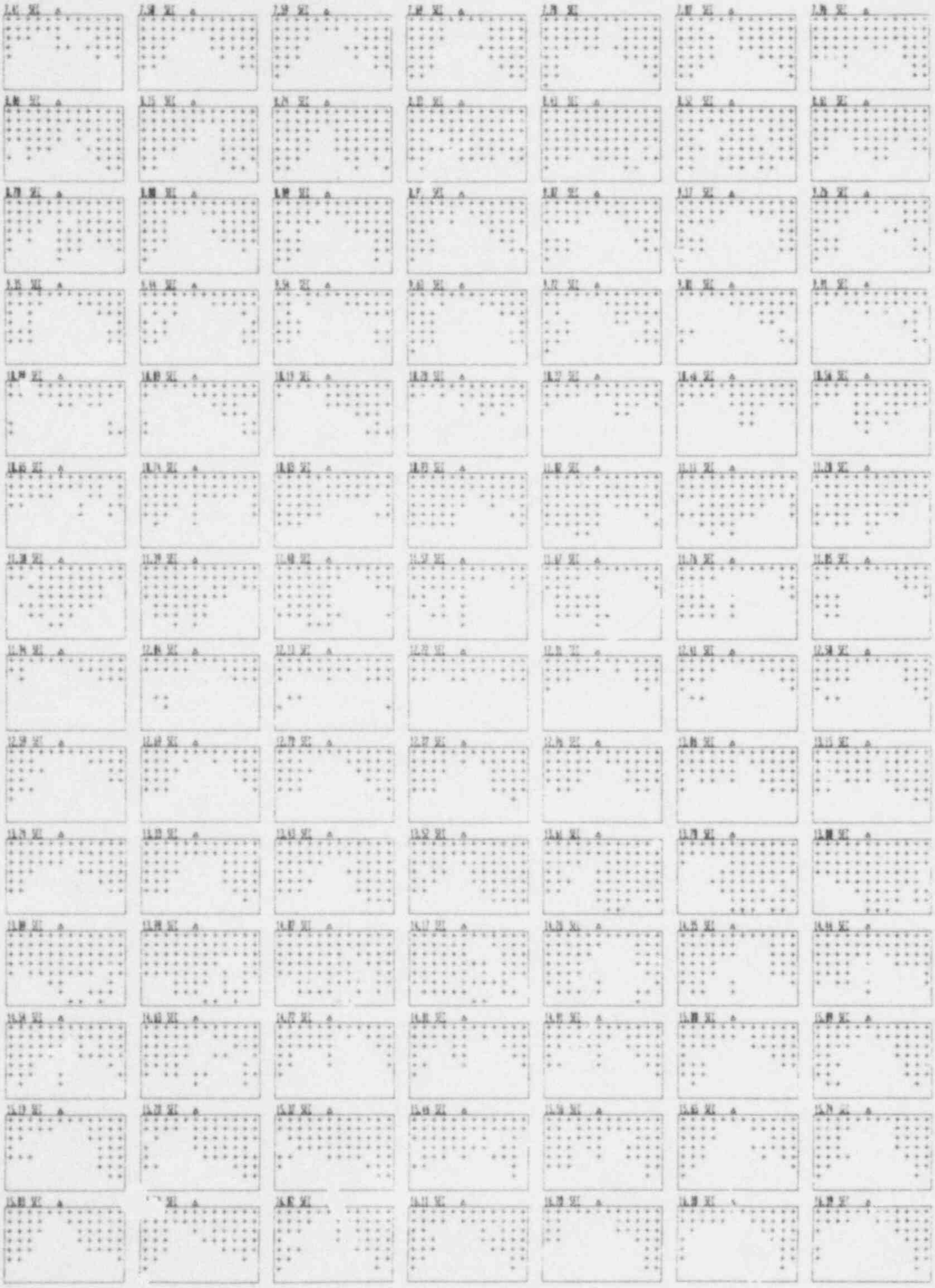


Figure 6. DATA FRAME SEQUENCE SHOWING ANNULUS OSCILLATIONS

3.2 Data Editing and Compression

The raw digital data frames recorded during countercurrent flow tests contain a significant amount of "random noise". That is, in addition to the relatively smooth and consistent motion of larger masses of water, there is much rapid flickering of scattered sensors. This fact is not the result of errors in the recording equipment; the violent nature of the countercurrent flow process produces sprays, mists, and droplets moving rapidly in all directions. It is usually desirable to suppress this element of the data in order to obtain a clear view of the dominant large scale motions.

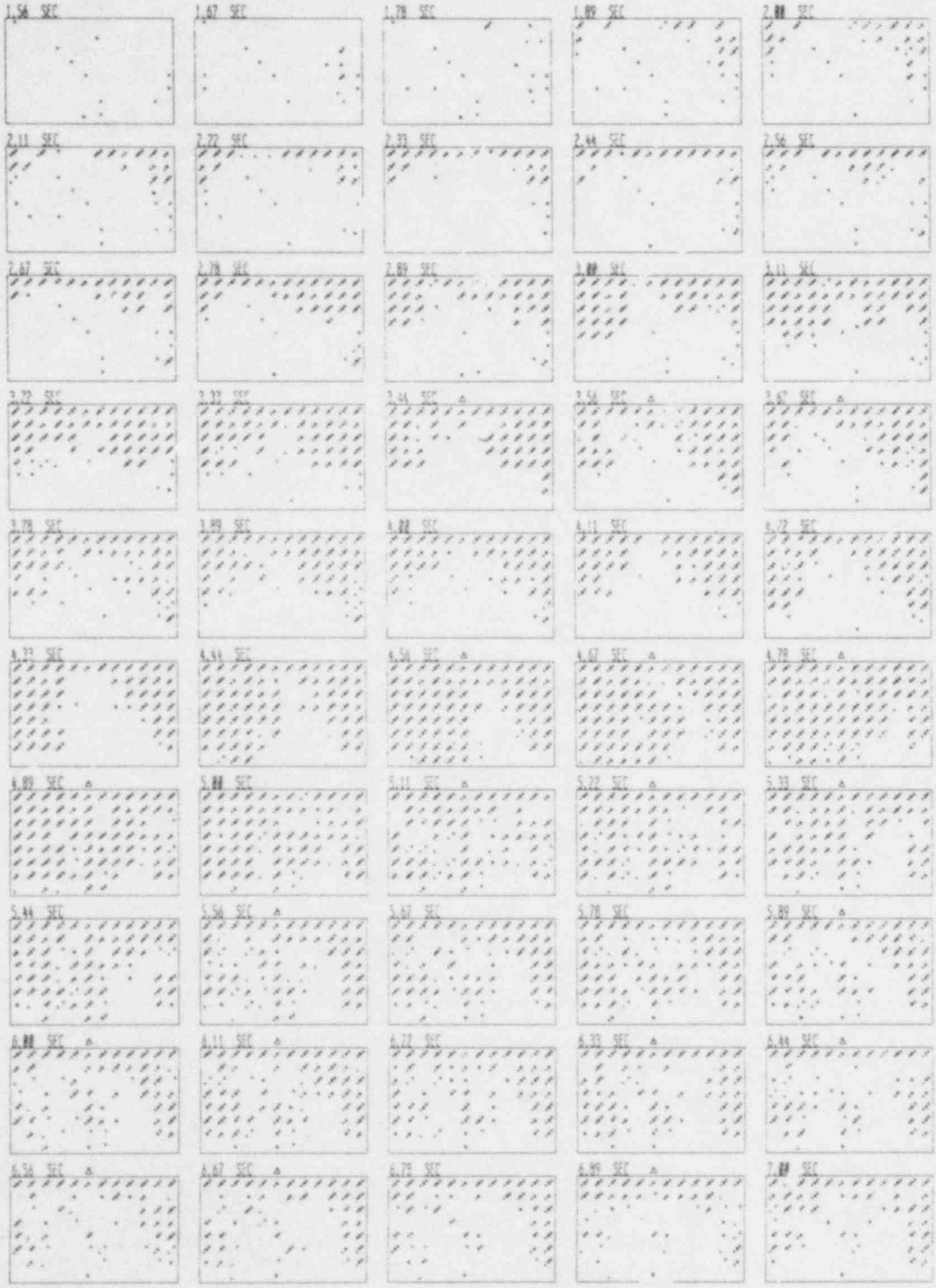
It has proven useful to apply one or more forms of editing to the recorded data to heighten the contrast of the images. The basis for this editing is the assumption that significant steam and water masses will be detected by several adjacent sensors. First the data bits from each of the 96 probes are examined separately; all of a probe's bits are reset unless they meet user-specified requirements as a group. For instance, it could be required that the center sensor and at least one other sensor be on, or that all three sensors be on. After that, each probe is reset unless a specified number of adjacent probes match its current state. Values for editing control parameters can be chosen to suppress entities and topography features which are less than a specified minimum size. Editing affects displays and computed quantities only; the data files are not altered.

An example of the effect of editing is shown in Figure 7, which presents a sequence of data frames recorded at 0.11 second intervals. In 7a the data are shown unedited. The data sequence begins prior to the injection of fluid, and the randomly scattered probes which appear in the first few frames are actually responding to steam condensing on the cold metal surfaces of the sensors. In 7b, automatic editing has been applied. The frames remain blank until the time of injection, and during the remainder of the sequence the advance and subsequent retreat of the water mass is more clearly outlined than in the raw data. In this example, the editing never increases the number of sensors in the on state, it always turns off sensors which are relatively isolated. Most of the examples of test data shown in this report and in the accompanying film have been subjected to editing of this type.

This particular example of an editing mode suppresses small and isolated liquid entities. The same algorithm can be applied in the reverse sense to eliminate small steam entities appearing within larger liquid masses. Because the individual data bits are readily associated with details of probe and vessel geometries, editing and sorting operations of many types are easily implemented. For example, film flow and chaotic flow during regime transitions can be characterized and automatically detected.

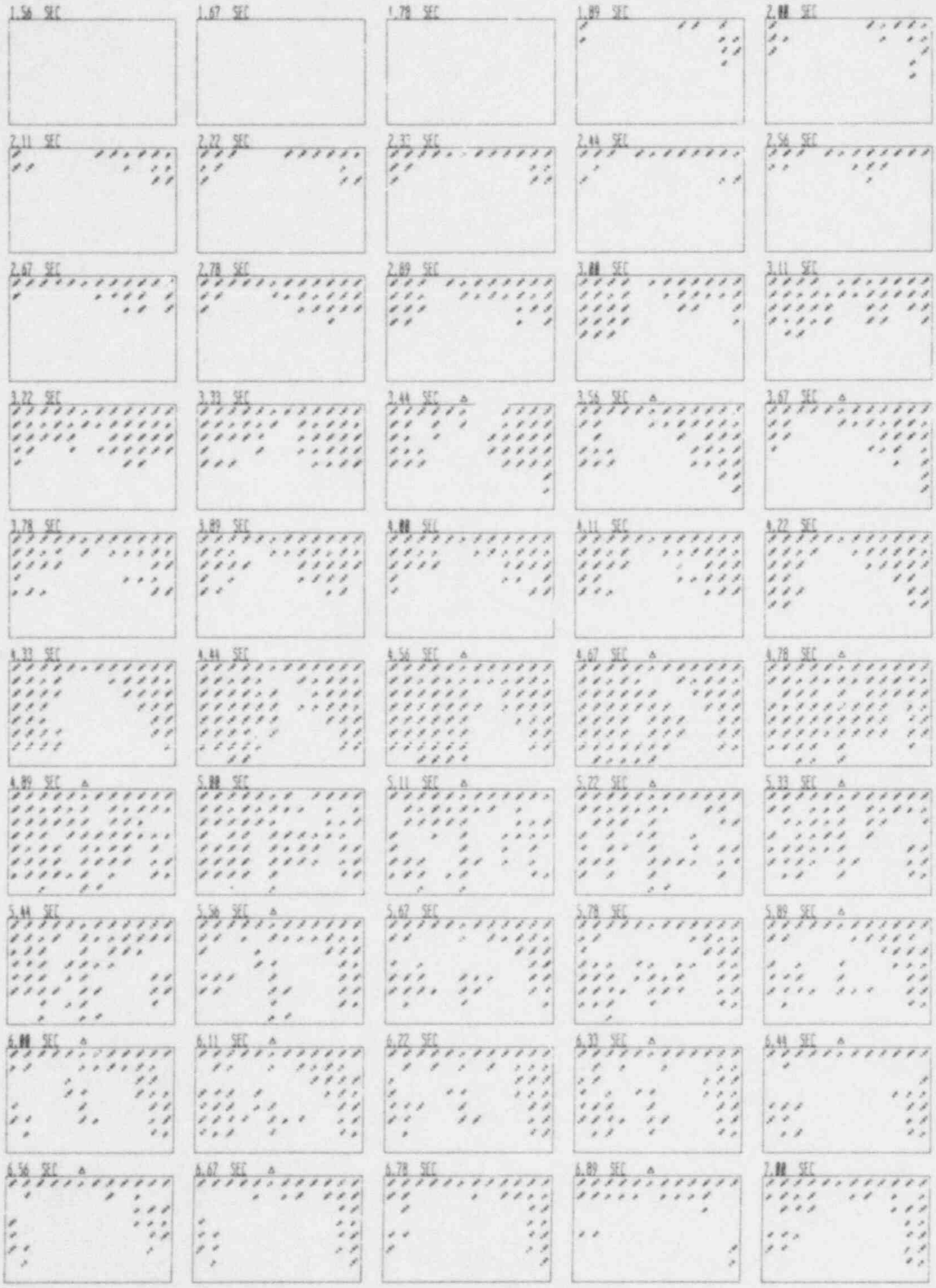
Because editing can define an on/off state of each of the 96 probes, it also acts as a form of data compression. In many cases the third dimension (across the annulus gap) is of secondary interest. A data representation which uses one symbol for each probe can be more easily interpreted by the eye or by software, and more compact displays are achieved. The phase interface locaing routines which we have applied to countercurrent flow data work exclusively with two-dimensional data.

POOR ORIGINAL



a) Raw data showing random elem.nts

Figure 7. EXAMPLE OF DATA EDITING PROCEDURE (TEST ST401D)



b) Images clarified by automatic editing

Figure 7. EXAMPLE OF DATA EDITING PROCEDURE (TEST ST401D)

3.3 Films

A standard video terminal is not able to display data frame images rapidly enough to produce a good illusion of motion, nor can it provide the required blanking and speed control. In order to reproduce recorded flow processes at their true speed and at controlled slow motion rates, the terminal can be synchronized with the action of a camera in order to transfer a sequence of images to the successive frames of a roll of movie film. A 16mm camera equipped with a single-frame motor drive is mounted in front of the screen of a color video terminal. The computer displays one frame of data on the terminal, triggers the camera to expose one frame of film, and repeats the sequence until a full roll of film has been exposed. The process is automatic and requires no operator attendance. Data frames are normally recorded at the rate of 108 per second. If every recorded frame is transferred to film and then projected at 18 frames per second, a 6X slow motion effect will result. To observe a test at its true speed, a film can be generated using every sixth recorded data frame. Several films using various display formats have been prepared by this method. The most recent one presents full speed and slow motion views of several countercurrent flow tests and includes both raw data and computer-generated phase interface lines. This film is described in Appendix B.

Among the drawbacks of using film to reproduce recorded tests are the lengthy time required to expose and process the film and the fact that there is no way to preview the results. Machines exist which can transfer data from magnetic tape to film at high speed, but they are very expensive and therefore not generally available. By using special interface hardware it would be possible to recreate recorded flow processes directly on a video monitor at full-speed or in slow motion, thereby eliminating the camera and film altogether. Tests could be played back immediately from computer memory and recorded with a standard video tape recorder. This method will provide an attractive alternative for future implementations of flow topography recording systems.

3.4 Pressure Data

During each test the signals from four pressure transducers are digitized and recorded 50 times per second. Gage pressures are recorded in the lower plenum and in the upper annulus near the break, and differential pressures are recorded horizontally across the top of the annulus and vertically between the top of the annulus and the lower plenum. These data supplement the topography recordings and open the possibility of relating specific liquid/vapor interface motions and changes in flow patterns to corresponding pressure events. In principle, a larger number of pressure signals could be correlated with the topography data to provide fine detail.

Figure 8 presents the raw pressure traces recorded during a countercurrent flow test with fluid injected at 40 gpm and with relatively low reverse steam flow. It exhibits most of the features that are typical of these recordings. All the traces are dominated by a semi-regular oscillation at 2 to 3 Hz. The two gage pressures initially have an elevated mean value which decays to zero after four to five seconds as steam and water mixing reach equilibrium. The amplitudes of the oscillations diminsh abruptly after eight to ten seconds; it is at this time that delivery of water to the lower plenum begins. The amplitudes grow breifly near the end of the test when the lower plenum is nearly full of water. In tests with higher steam flows which bypass large amounts of water, the amplitudes of the oscillations remain constant (and relatively large) throughout the test. In order to detect smaller variations which correspond to motions of the

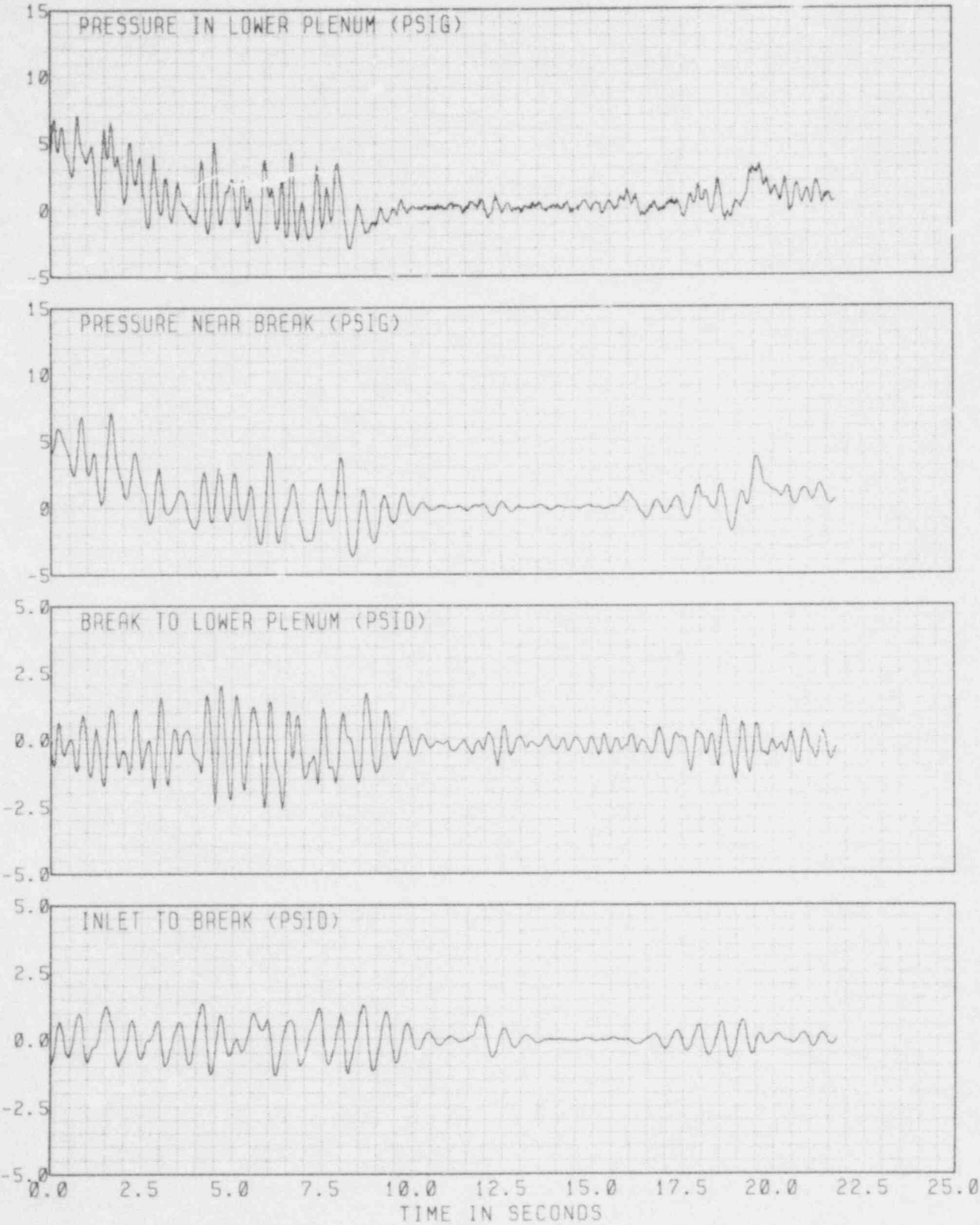


Figure 8. PRESSURE TRACES FROM COUNTERCURRENT FLOW TEST (ST401C)

steam/water interface it is necessary to remove the dominant oscillations by means of numerical filtering. Examples of the results obtained by doing so are presented in Section 4.6.

4 DATA ANALYSIS TECHNIQUES

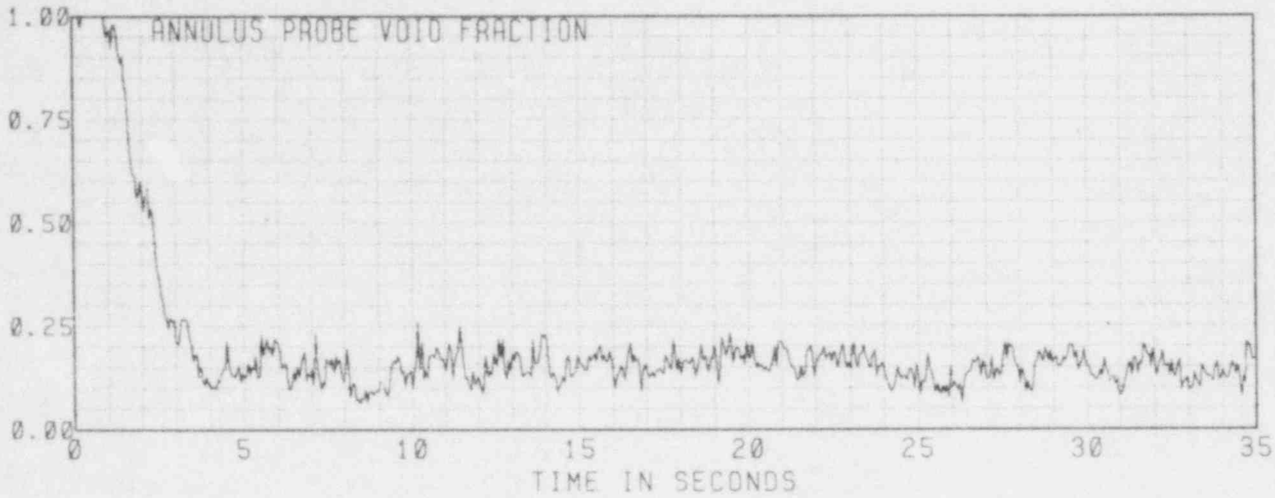
Because topography data is stored in numerical form in computer files, it can be processed to extract additional information beyond the purely visual element. This section describes examples of calculations that have been implemented and applied to recorded countercurrent flow data. It demonstrates for a specific application ways in which traditional engineering and numerical analysis methods can be combined with techniques developed specifically to deal with topography recordings. The particular techniques described here were chosen for their usefulness as applied to countercurrent flow data. Many of them will be useful in other applications, and many others can be implemented to meet specific needs. The sample results given also reveal a number of interesting facts, not previously recognized, which will contribute to a better understanding of countercurrent flow processes.

4.1 Probe Fractions

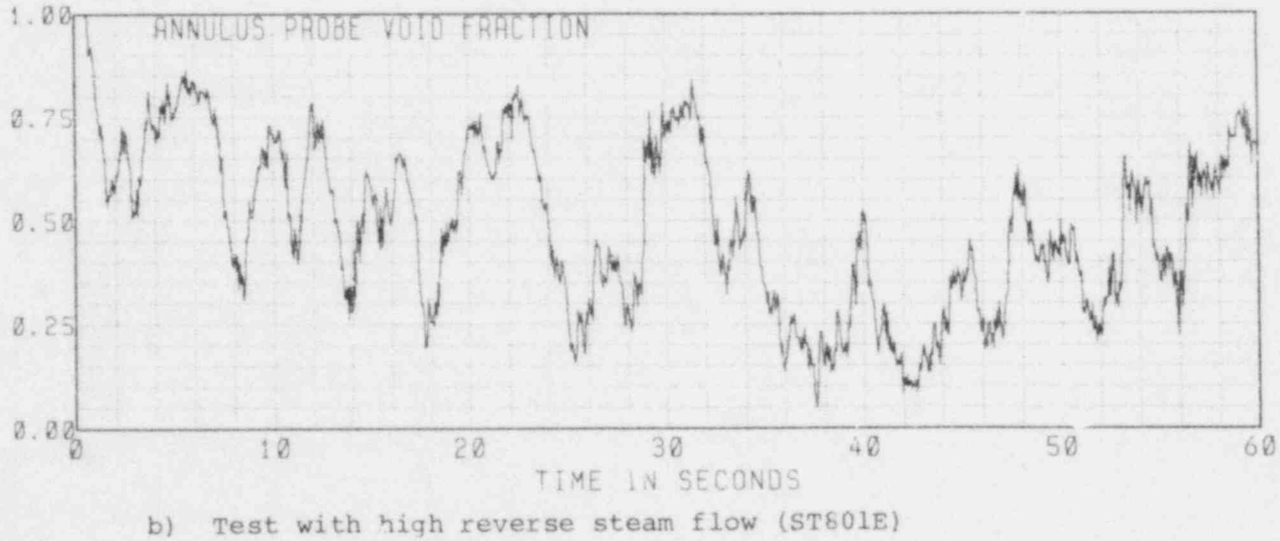
One simple and informative technique is the calculation of probe fractions; that is, the fraction of a particular set of conductivity sensors that are in a particular state. The fraction of sensors "on"is analogous to a liquid fraction, and the fraction "off" to a void fraction; probe fractions and true liquid fractions are not always strictly proportional to one another, but their relative variations have the same qualitative meaning. The choice between liquid and void fractions is one of convenience. In this report we have plotted probe void fractions wherever annulus data are discussed because graphs of that quantity are more intuitively pleasing to the eye; i.e., as water falls through the annulus, the corresponding void fraction falls with it. For lower plenum data, on the other hand, we frequently compute the fraction of probes on and interpret it as a measure of the lower plenum water level. As the water level rises, its corresponding liquid fraction rises as well.

Figure 9 shows two contrasting examples of annulus probe void fraction plotted as a function of time. In the first example, from a countercurrent flow test with very little reverse steam flow, the void fraction drops to a low value following injection and remains there. The injected water is falling unimpeded through the downcomer, causing most of the annulus sensors to remain immersed. In the second example, from a test with higher steam flow, the void fraction oscillates over a wide range of values in a semi-periodic manner. This signature is typical of countercurrent flow tests with high reverse steam flow. Its meaning can be understood by referring back to Figure 6, which shows a sequence of data frames from a portion of this test. Upflowing steam suspends the injected fluid in the upper portion of the annulus. At times the fluid mass expands to fill most of the downcomer, but it is subsequently forced back and out the broken leg. As with a mechanical spring-mass system, the liquid mass in the downcomer is bouncing on the compliant gas in the vessel in an oscillation driven by the instability of flooding in the downcomer. No water was delivered to the lower plenum during this test.

A concise history of a countercurrent flow test can be produced by plotting the annulus probe void fraction alongside its corresponding lower plenum probe liquid fraction. Comparison of the two curves shows the clear distinction between periods of bypass and periods of delivery and also shows how rapidly the transition between the two states occurs. Figure 10 is a good example. This test lasted 40 seconds altogether; delivery of water was confined to two sharply defined period each about six seconds in length. During these two periods the annulus probe void fraction drops abruptly to a small value, and the lower plenum water level rises steadily.



a) Test with low reverse steam flow (ST201F)



b) Test with high reverse steam flow (ST601E)

Figure 9. EXAMPLES OF ANNULUS PROBE VOID FRACTION

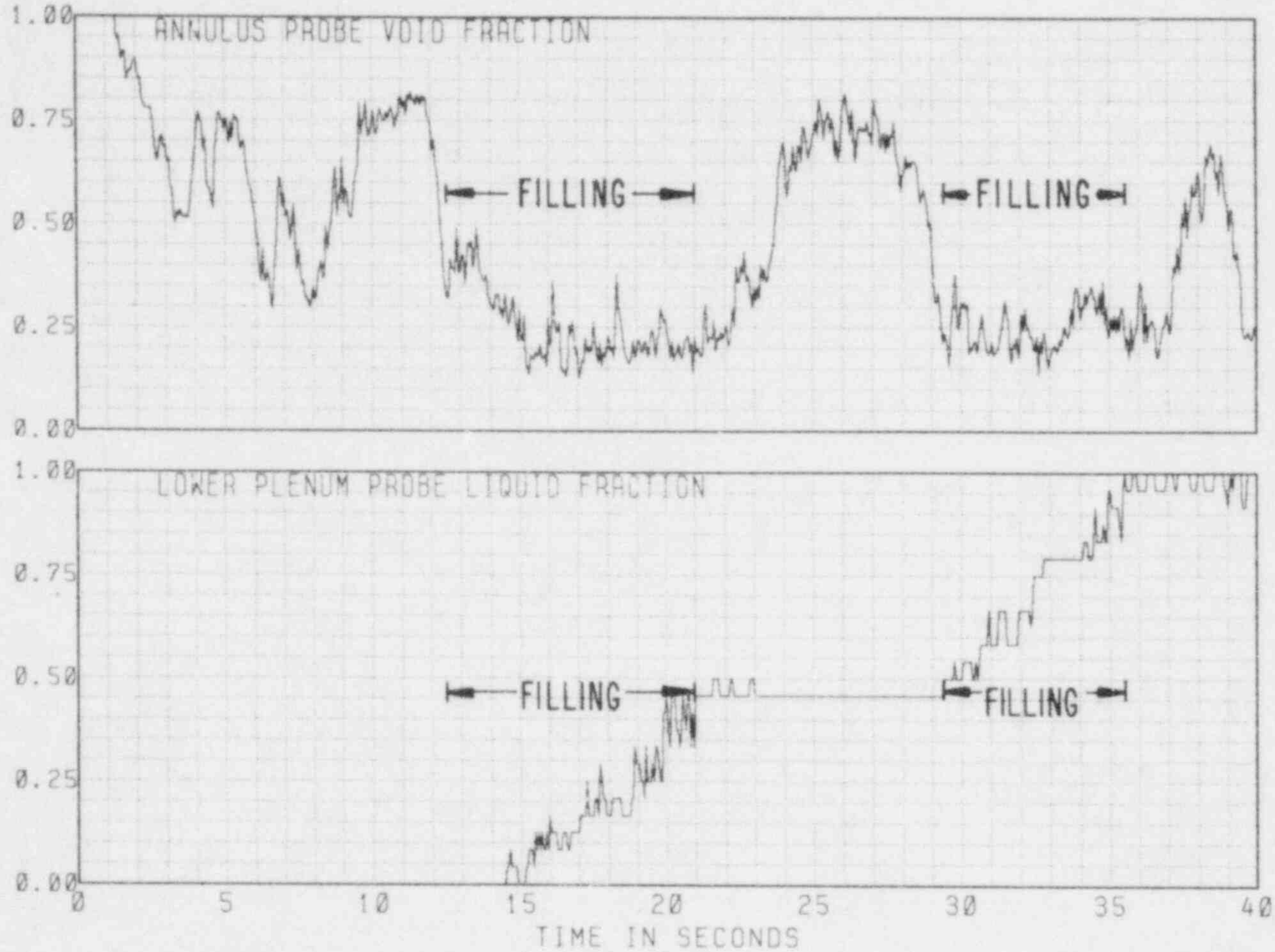


Figure 10. DOWNCOMER VOID FRACTION COMPARED TO PLENUM FILLING RECORD (TEST ST401F)

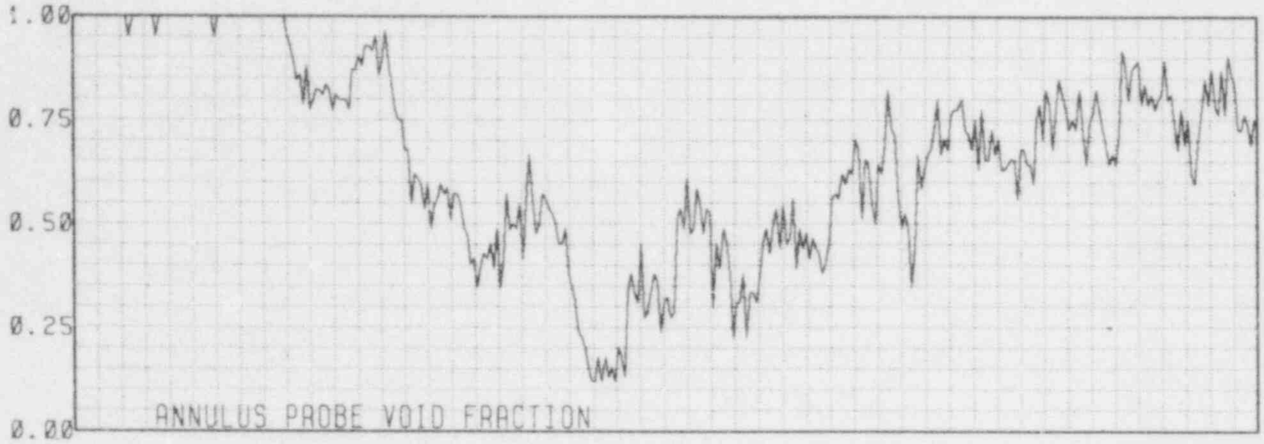
Each period of delivery is terminated when a large portion of the annulus (50%) is rapidly voided as the phase interface moves upward. As with all tests discussed in this report, steam and water injection rates were constant. It is interesting to note that while condensation interactions between the steam and water in the vessel produce pressure oscillations at 2 to 3 Hz, alternations between filling (or annulus storage) and bypass (or annulus voiding) typically occur at intervals of several seconds.

The examples given above compute fractions of the full annulus sensor set. Information about specific regions of the vessel can be obtained by computing fractions on subsets of sensors. For example, Figure 11 compares for a portion of a test the void fraction for annulus sensors near the break with the same fraction computed for sensors opposite the break. Four columns of probes are included in each fraction, and sensors above the injection legs are omitted. These curves verify an impression gained from watching the film produced from this test, that the region directly below the break tends to remain voided to a greater extent than the region on the opposite side of the annulus. An example of fractions computed in 16 local regions of the annulus is given in Reference 6. Local fractions computed from recorded data can be used to assess theoretical codes which partition the downcomer into nodes. Miniature sensors installed throughout a large vessel would permit detailed mapping and calculation of fractions for a large number of nodes. Another type of fraction that can be computed separates near-wall sensors from center-of-gap sensors to specifically detect formation of wall films. An example of such a calculation is also given in [6]. Many other forms of sensor fractions could be implemented to meet the needs of specific applications; e.g., to detect flow stratification, and so forth.

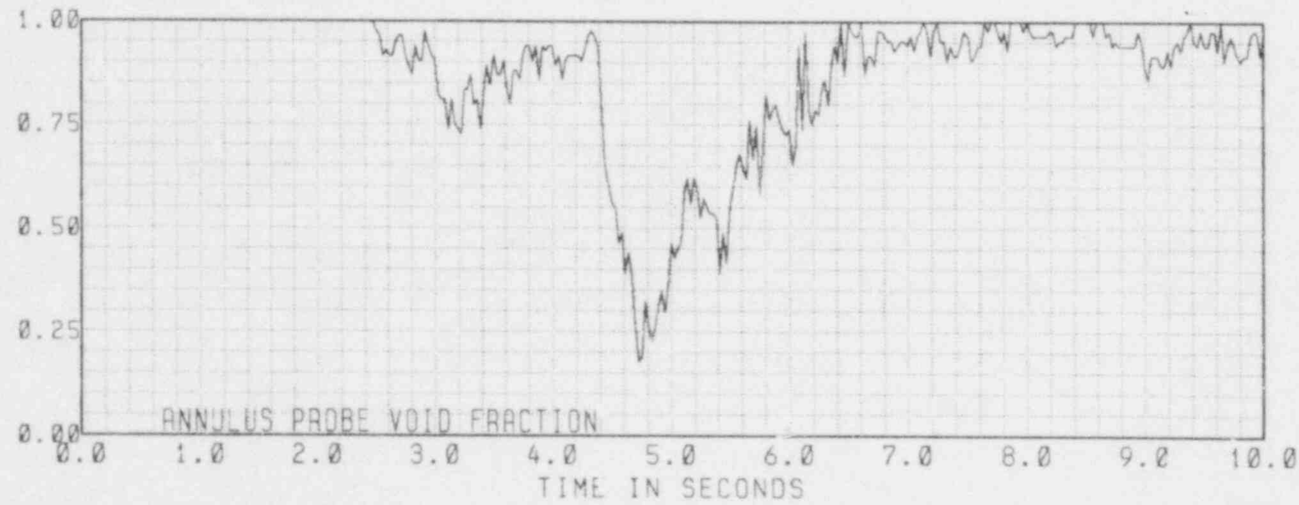
4.2 Phase Interfaces

In the simplest sense of the term, detection of phase interfaces in topography data frames is not difficult. The computer can quickly locate and flag all local phase transitions in a single data frame, producing a set of closed curves which surround all the distinct steam and water entities. Much more challenging is the problem of separating the interface elements which are meaningful from those which are essentially random, highly transient, or otherwise irrelevant within the context of the application. It can also be difficult to identify interface elements appearing in a sequence of frames in a consistent way that permits calculation of realistic interface velocities. Automating these latter operations requires the use of heuristic pattern-analysis algorithms, for which there exist very few systematic design techniques.

The choice of what is meaningful depends to a large degree on the application, specifically on the time and space characteristics of the flow and on the information that is sought from the analysis. In some applications, for example, attention may be focused on small entities, such as bubbles or droplets, with extended surfaces being of secondary interest. In other cases the priorities will be reversed. The details of the interface processing algorithms and the choice of numerical analysis tools to be used in conjunction with them will be dictated by considerations of this kind. By focusing on specific analysis goals the magnitude of the required software development effort can be minimized.



a) Opposite break



b) Near break

Figure 11. LOCAL DOWNCOMER PROBE VOID FRACTIONS (TEST ST401D)

In the following sections we consider a specific application—countercurrent flow in a PWR model—and provide examples of data analysis techniques appropriate for that application. Based on visual observation of data displays a first order model is postulated. An algorithm which locates interfaces consistent with the model while suppressing extraneous features is described, and sample results are shown. Interface velocities are computed and shown to have realistic magnitudes. Interface motions are shown to be directly correlated with delivery of water to the lower plenum and with observed pressure variations. These results provide useful information about countercurrent flow and serve as an example of a set of analysis tools addressed to a specific application of the system.

4.3 Automated Location of Interfaces

Prior to the implementation of the Flow Topography system, little was known about the details of the interaction between the steam and water within the annulus during scale-model countercurrent flow tests. The principal data available were time-averaged delivery rates and plots of lower plenum water level as a function of time. The latter had shown that in many cases delivery rates were not constant, and that water tended to be delivered in bursts (slugs) separated by periods of no delivery. The availability of flow topography data recorded in the Creare demonstration vessel has permitted direct observation of the annulus flow processes. Examination of data from representative tests has shown that under conditions which produce a significant amount of fluid bypass, the motion of the steam and water within the annulus can be described by the following model:

1) The steam and water are separated crudely by a single interface surface into two disjoint regions.

2) The water tends to remain compacted in the upper portion of the annulus while the lower portion is filled with steam.

3) The separating interface moves up and down in the annulus in a semi-periodic manner; if the interface reaches the bottom of the annulus, delivery of fluid to the lower plenum may occur.

This picture is an idealization since smaller isolated water masses are frequently seen as well as steam bubbles moving within predominately water filled regions. It remains true that upon looking at an isolated data frame one can usually draw a single line that makes a very reasonable separation of steam from water. (The interface is actually a surface, but to simplify the calculations in this example we will ignore the third dimension across the narrow annulus gap.) Furthermore, if one draws this line in each of a sequence of frames, it is seen to move in a consistent manner that clearly represents the motion of a true physical interface. Interfaces surrounding smaller entities are principally random and non-persistent, and they contribute less directly to an understanding of the dominant flow regimes.

Although it is usually easy for a human being to define an interface line which satisfies this model for a given data frame, the very large number of frames recorded during even a single test makes it impractical to do so for any significant amount of data. It is more practical to use a computer algorithm to automatically locate the interface line without human assistance. The speed of such an algorithm depends upon the complexity of the underlying model, but a processing rate of about 10 data frames per second is typical. Without going into great detail, the sequence of operations for an algorithm based on the countercurrent flow model given above is as follows:

1) Data editing of the type described in Section 3.2 is performed in order to clarify the image and reduce the problem to two dimensions.

2) All steam/water boundaries are located and grouped into a set of closed loops. These loops surround steam and water entities of various sizes.

3) Isolated loops which surround entities of less than a specified size are eliminated.

4) Remaining edge segments which do not belong to the principal border are eliminated. (This cleans up indistinct portions of the interface in an arbitrary way.)

5) If the final interface fails to meet certain conditions, it too is eliminated. (The annulus is considered to be completely full or completely empty.)

This procedure usually results in a single line which is close to the one that would be drawn by a human. It works best, of course, on data frames in which the steam and water are well segregated. Even in frames which lack a clearcut interface, the routine usually produces independently reasonable solutions. However, in extreme situations during periods of developing flow regimes, a change in the states of only one or two probes can produce a major change in the position of the interface. While each solution is consistent with the probe data, it would be wrong to conclude that a rapid motion of a true interface had occurred. These high speed and high frequency fictitious motions can be exploited to identify alteration of the governing flow regime.

We present some sample results produced by the routine described above to demonstrate the general style and quality of one class of interface solutions. Figure 2 shows a sequence of frames in which a well-defined mass of fluid expands until it fills most of the annulus. There are no serious ambiguities in these frames, and the interface solutions are straightforward. Figure 12 shows a longer sequence that presents the interface locator with some more difficult cases. These frames were recorded at 0.11 second intervals, so each horizontal row spans an interval of 1 second. This frame sampling rate (9 per second) is usually adequate for observing large-scale motions. If the reader carefully follows the motion of the interface through this sequence of frames, he will see that (with occasional exceptions) it moves in a regular and consistent way, tracking the alternating advance and retreat of the suspended water mass. The continuity of the solutions is further confirmed by Figure 13, which shows every data frame recorded during a 1.33 second interval of this test. The frames in the seventh and part of the eighth row of Figure 12 appear as every twelfth frame in Figure 13. The frames shown in this figure are recorded at intervals of less than 0.01 seconds and are therefore somewhat redundant. In the latter part of this sequence the flow becomes somwhat chaotic as the annulus begins to be rapidly voided, and the so-called "water-filled" region is sometimes 30-40% steam. This algorithm is constrained to produce a single interface, and it does the best it can under the circumstances. The solutions become more arbitrary, and in some cases the code is "fooled" into giving a rather poor result.

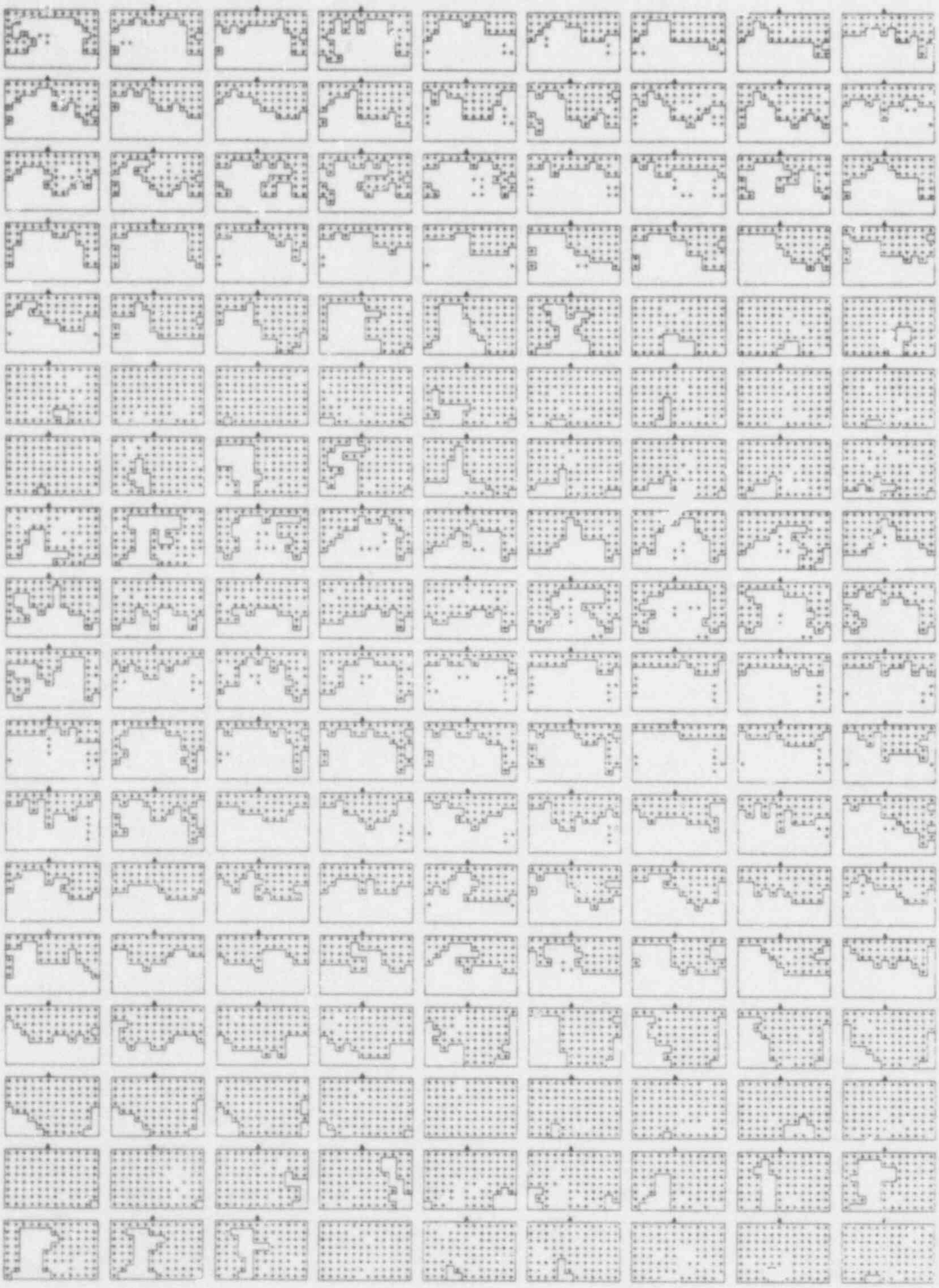


Figure 12. DATA SEQUENCE SHOWING INTERFACE MOTION (TEST ST401E, FIRST FRAME AT 24.89 SECONDS, FRAMES AT 0.11 SECOND INTERVALS)

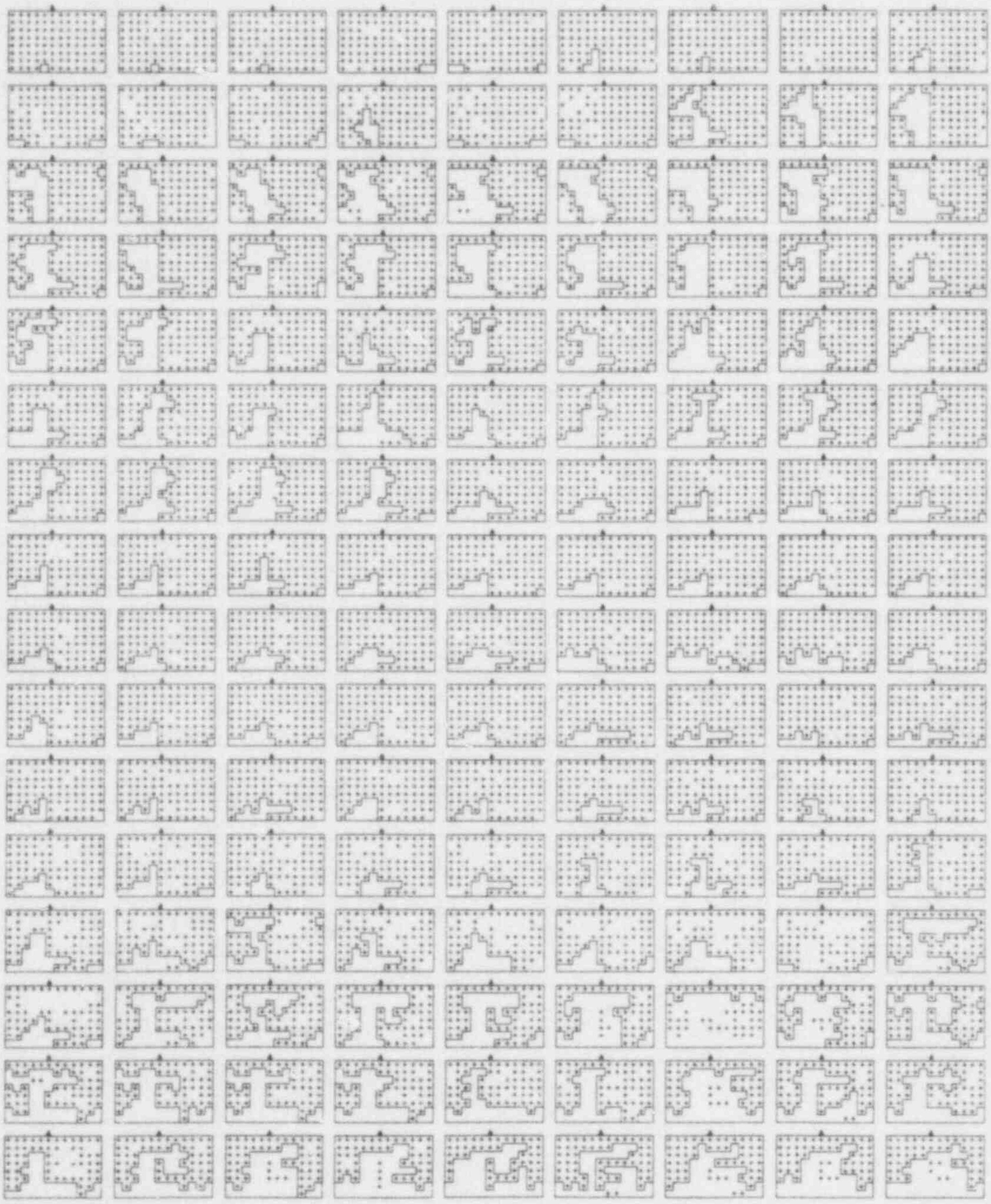


Figure 13. DATA SEQUENCE SHOWING CONSISTENCY OF INTERFACE SOLUTIONS (TEST ST401E, FIRST FRAME AT 30.89 SECONDS, FRAMES AT 0.01 SECOND INTERVALS)

Figure 14 shows a sequence that is difficult for the single-interface algorithm to deal with. During the period shown, the distribution of fluid is roughly constant; no consistent motion by a well-defined interface is apparent. More or less random changes in state by a few scattered probes cause the groups of probes in the lower part of the annulus to become alternately attached to and detached from the body of fluid above. This produces two classes of interface solutions which alternate irregularly. This data sequence would be handled better by a more sophisticated algorithm which permitted multiple liquid masses to alternately merge and re-separate. As this example shows, insufficiency of an algorithm for a specific need is usually readily identified.

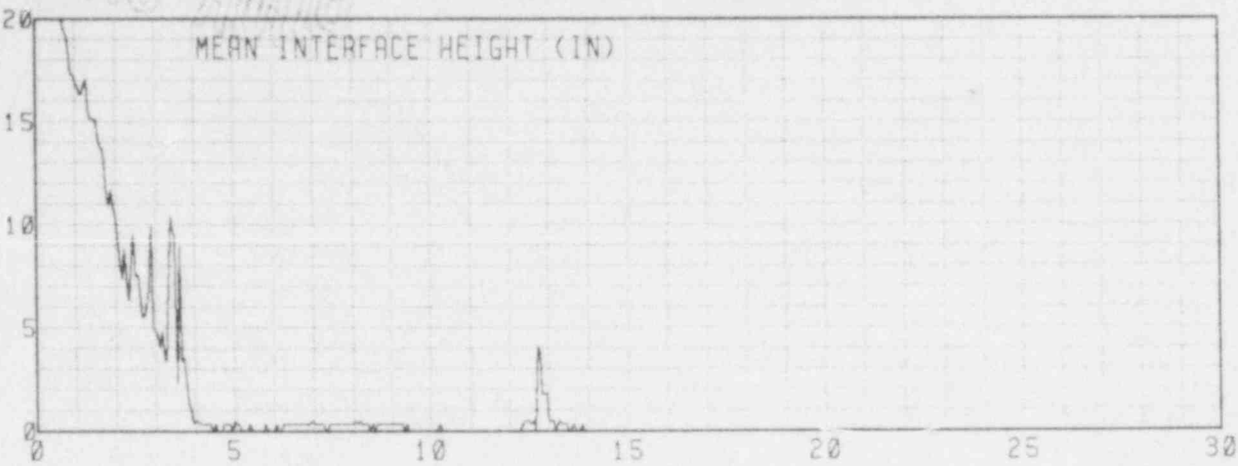
4.4 Interface Height and Plenum Filling

The computed phase interface is stored in the form of a table of short edge segments which link together to form the complete interface. The coordinates of each segment are known, and it is possible to compute quantities which describe the interface such as mean height, total vertical extent, mean and total horizontal extent, and so forth. In general, any function of the interface segment coordinates which is of interest in a particular application can be computed.

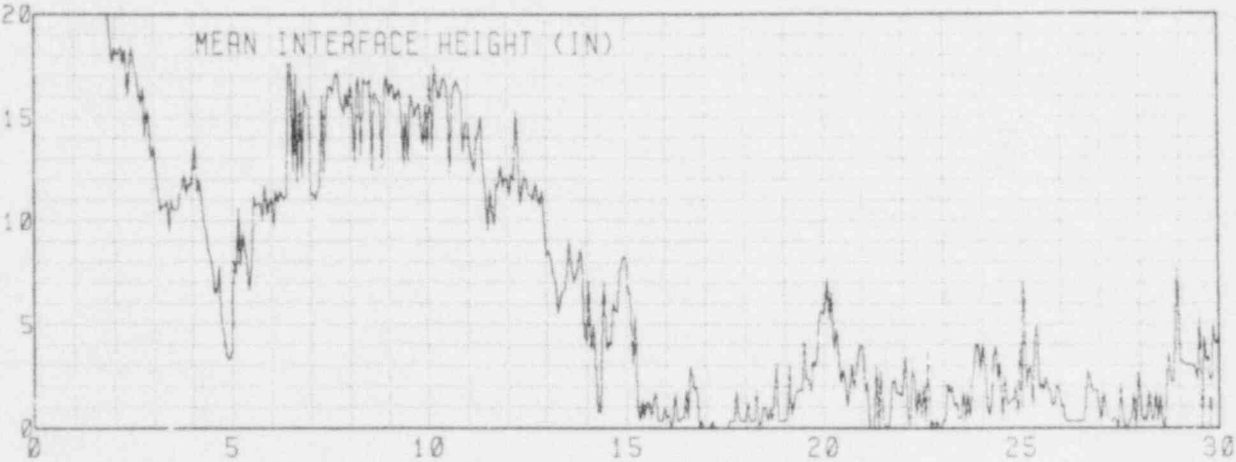
The flow of the injected water during countercurrent flow tests has both vertical and horizontal components. Application of the model discussed in the previous section locates a single extended interface whose principal motions are vertical. Vertical liquid motions can be characterized by the vertical motions of the interface. Horizontal liquid motions can be calculated by determining the vertical cross-section implied by the local interface height and the void fraction implied by the probe fraction within the region above the interface. An interface algorithm which focused on smaller entities would permit analysis of fine scale motions such as circulatory patterns. Retaining the three-dimensional character of the data during interface location would allow distinction between film and slug flow.

To provide a concrete example of the analysis of interface characteristics we will continue our discussion of the model given in the previous section, relating the vertical motions of the interface to plenum filling and to observed pressure variations. Figure 15 presents graphs of the mean phase interface height as a function of time for a sequence of three steady-state countercurrent flow tests. The fluid injection rate was 40 gpm for all tests; reverse steam flow was fixed during each test but increased from one test to the next. Part (a) is from a test with relatively little steam flow. The interface moves steadily downward (except for a brief fluctuation) until it reaches the bottom of the annulus at 4 seconds (about 3.5 seconds after injection), when plenum filling begins. Since water moving under the influence of gravity alone falls through the annulus in less than half of a second, the upward steam flow has substantially slowed its progress. In part (b) the steam flow has been increased. In this test the downward progress of the interface is reversed after a few seconds. It returns to the upper part of the annulus and remains suspended there for several seconds before it again moves downward in a somewhat jerky fashion, finally reaching the bottom of the annulus at about 15 seconds. Part (c) is from a test with much higher steam flow. Immediately after injection and on two later occasions (at 18 and 30 seconds) the interface drops to a low level, but in each case it quickly moves back up. Finally, at 40 seconds, it completes its final downward trip and plenum filling begins.

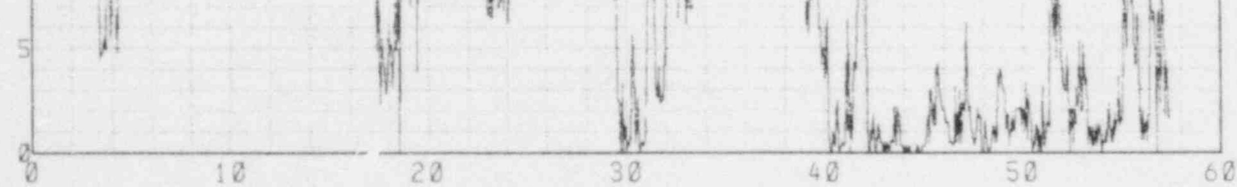
Figure 14. COMPLEX FLUID DISTRIBUTION NOT WELL MODELED BY SINGLE INTERFACE (TEST ST801E)



a) Test ST401B - low steam supply rate



b) Test ST401D - moderate steam supply rate



c) Test ST' J1E - high steam supply rate

Figure 15. MEAN PHASE INTERFACE HEIGHT

Figure 16 shows a plot of the lower plenum water level (expressed as a probe liquid fraction) for the test whose interface height is plotted in Figure 15b. Filling of the lower plenum begins at 15 seconds when the interface first reaches the bottom of the downcomer. The volume spanned by the lower plenum probe stalk is 9.5 gallons. The graph shows this volume being filled in 14 seconds, so water is being delivered at the full injection rate of 40 gpm. Each of the three tests shown in Figure 15 exhibits two distinct phases: (1) an early period of bypass and/or storage, followed by (2) a period of steady delivery at the injection rate. In the third test the interface appears to briefly touch the bottom at 30 seconds, and in fact a very small amount of water was delivered at that time. The minor deviations of the interface height from the zero level during delivery show that small portions of the annulus are continuously being voided, but filling is not interrupted.

A contrast to this behavior can be seen in Figure 17, which shows data from a test with water injected at 80 gpm and with very high steam flow. Throughout this test the interface height oscillates over a wide range of values; water is alternately being stored in the annulus and then forced out the break. The interface reaches the bottom of the annulus briefly at two times, at about [illegible] and 42 seconds, producing two brief but large slug deliveries. After that, the interface moves upward in the annulus, and there is no further delivery. The fact that the first slug delivery commences slightly before the value of the mean interface height reaches zero is the result of asymmetric delivery. The portion of the interface opposite the break reaches the bottom of the annulus, and delivery begins while the remainder of the interface still has a positive height. This can be demonstrated either by displaying full data frames or by examining the mean interface heights in selected regions of the annulus circumference.

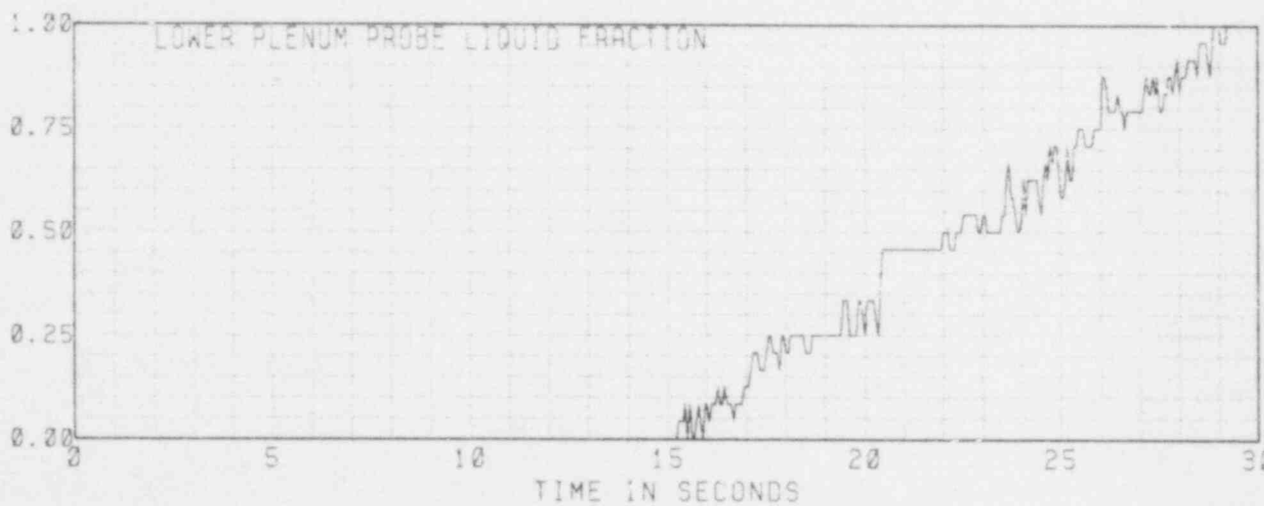


Figure 16. <u>PLENUM FILLING RECORD FOR TEST ST401D</u>

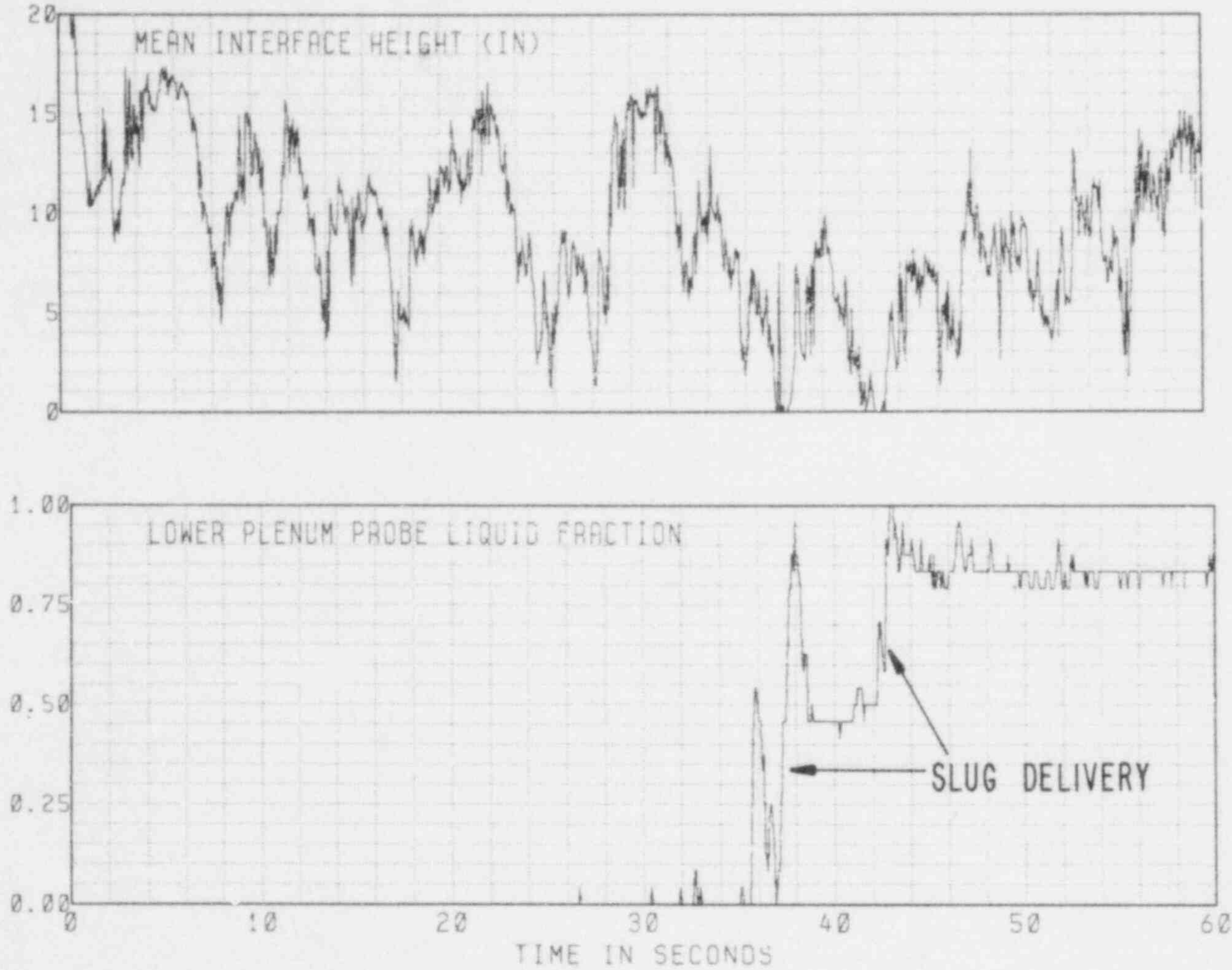


Figure 17. MEAN INTERFACE HEIGHT AND PLENUM FILLING RECORD FOR TEST ST801E

4.5 Filters and Interface Velocities

In this section, we describe our approach to some specific difficulties encountered in interface definition for the ultimate purpose of calculating interface velocity. The digital filtering method illustrated here by its application to interface height can also be applied to the raw data (Section 4.6). The unavoidable high frequency variations that arise because of the discrete nature of the interface location process (regardless of the algorithm chosen) make filtering an important step in the analysis of virtually all flow characteristics computed from the interface solutions.

The plots of interface height have both low and high frequency components. This is in spite of the fact that editing as described in Section 3.2 was first applied to suppress random elements in the data. Furthermore, the interface calculation is itself a smoothing process since it attempts to locate a large, well-defined liquid mass. A close look at a representative data sample will help explain the sources of high frequency components, which for present purposes we treat as "noise". Figure 18 expands an 8-second segment of Figure 15c. Whereas the graph for the full test included only every sixth recorded data frame, this graph includes all data recorded during the period shown (108 frames per second). During the first two seconds and last two seconds shown, the curve is relatively smooth. The noise level seen during these periods is a realistic reflection of small scale jitter in the true interface. The center portion of the curve exhibits high-frequency oscillations of a much larger magnitude. This is a period of ambiguous data with respect to the interface definition employed, similar to the frames shown in Figure 14 and discussed in Section 4.3. The overall liquid distribution is relatively stable, but changes in the states of a few scattered probes cause major changes in the interface solutions. The "noise" observed during this period does not reflect rapid oscillations of a true phase interface; it occurs because the data are not well characterized by the assumption that a single interface will partition the annulus into steam and water-filled regions.

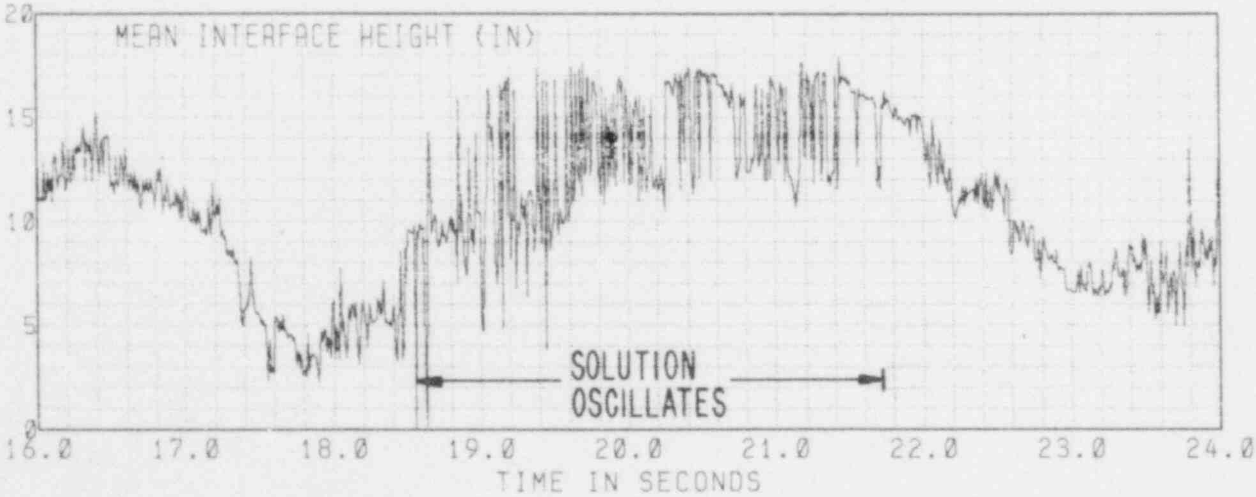
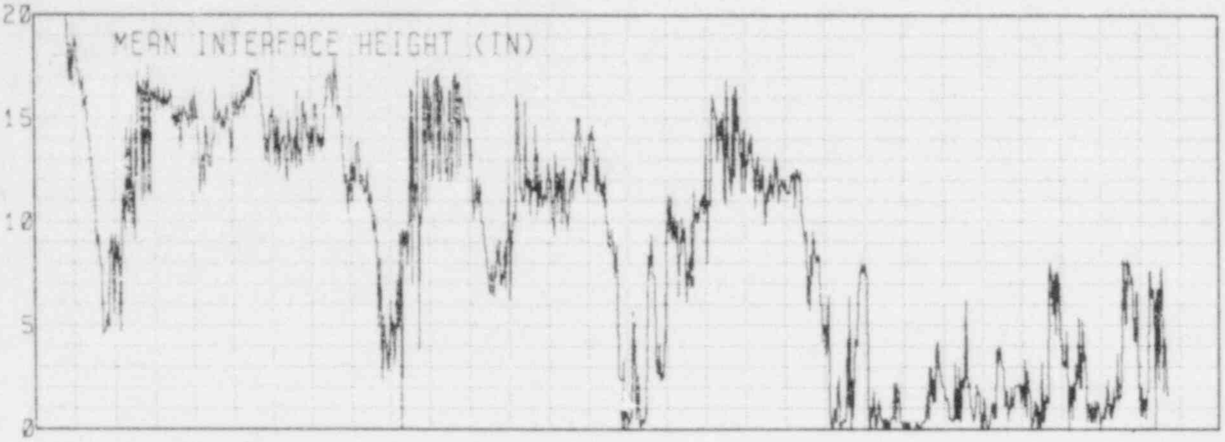


Figure 18. OSCILLATING INTERFACE SOLUTION (TEST ST401E)

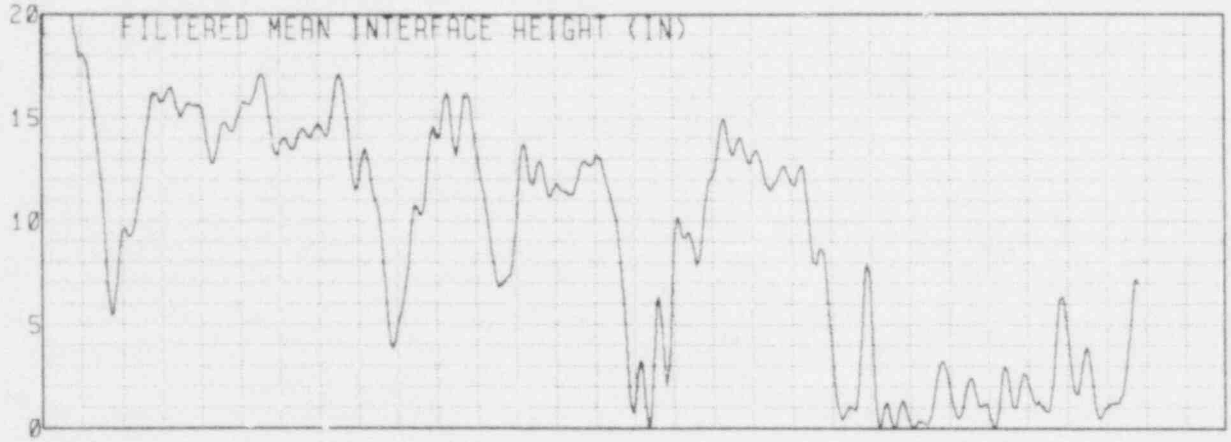
Meaningful large-scale interface motions occur typically at intervals of several seconds. These are overlayed and to some extent obscured by the high-frequency components. It is often useful to suppress the high-frequency content of recorded and computed quantities in order to better resolve their long-term behavior and allow their significant motions to stand out more clearly. Furthermore, smoothing must be performed prior to calculation of velocity elements by means of numerical differentiation. To obtain smoothed versions of interface height and other quantities we have utilized digital filters, which are computational analogues of the band pass and band-rejection filters used to remove unwanted frequency components from electrical signals. A function which is to be filtered consists of a long vector of raw values associated with a sequence of equally spaced times. The filter itself is implemented as a shorter list of constant coefficients; one filtered point is obtained by forming the inner product of the filter coefficients and an equal number of raw data values. Coefficients which produce the desired filter characteristics can be computed by means of the techniques described in [11]; computer routines have been implemented to perform these filter design calculations. For the present application we have utilized low-pass filters; i.e., those which reject all frequencies above a specified cutoff value.

Choosing the proper cutoff frequency for the low-pass filter to be used in the present application can be difficult for the following reason. Although high-frequency components contribute principally to the noise element of the interface height curves, they are also needed to accurately represent the abrupt motions of the real interface. Figure 19 shows the raw interface height curve originally presented in Figure 15c followed by two filtered versions of the same curve. The latter figures were produced by passing the original curve through low-pass filters with cutoff frequencies of 1.0 and 0.5 Hz, respectively. Both versions clearly show the major vertical motions of the interface and suppress most of the extraneous oscillations. Using the 1.0 Hz cutoff leaves details in the upper portions of the curve which may not represent real motions, while the 0.5 value in at least one place (just after 30 seconds) omits real motions. Filter cutoff frequencies must be chosen to suit the needs of specific applications. In the present case we wish to focus on the discrete large-scale motions of the extended interface. The curve produced by the 0.5 Hz filter displays these events clearly and is used as the basis for the following velocity calculations.

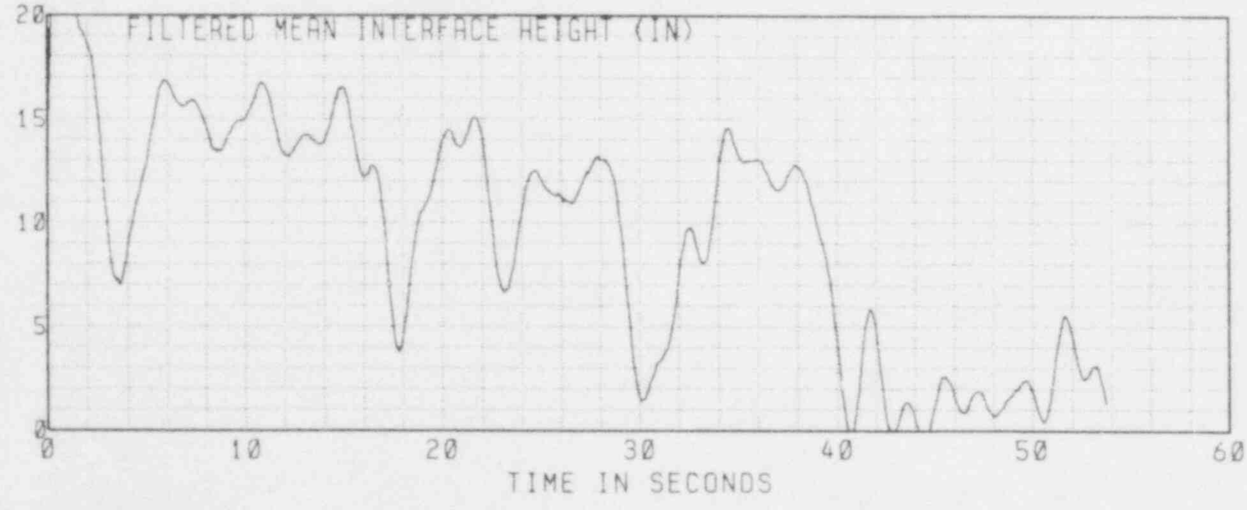
Routines were implemented to numerically differentiate the filtered interface height curves using the method of [11], which is a direct extension of the filtering calculation. In our example the calculation provides a measure of the vertical speed of the extended phase interface. More precisely, the quantity computed is the rate of change of the mean interface height, the vertical interface velocity averaged around the circumference of the vessel. In an application which used a more sophisticated interface algorithm, horizontal and vertical velocity components of discrete entities of various sizes could be computed. Figure 20 shows the result of differentiating the filtered interface height curve of Figure 19c. During this test the major interface motions comprise five discrete excursions, at 4, 18, 23, 30, and 40 seconds. The computed velocity has a mean value near zero (because the interface remains in the annulus for an extended time); oscillations with amplitudes on the order of ± 10 ips correspond to the major motions noted. (The initial transients prior to 1 second in Figure 20 and 21 result from the derivative calculations and do not correspond to real motions.) Table 1 summarizes, for the upward and downward portions of each excursion, the mean and peak velocities observed, in inches/sec. The last upward motion is omitted because it is



a) Unfiltered function



b) Filtered with 1.0 Hz cutoff



c) Filtered with 0.5 Hz cutoff

Figure 19. INTERFACE HEIGHT SMOOTHED BY DIGITAL FILTERING (TEST ST401E)

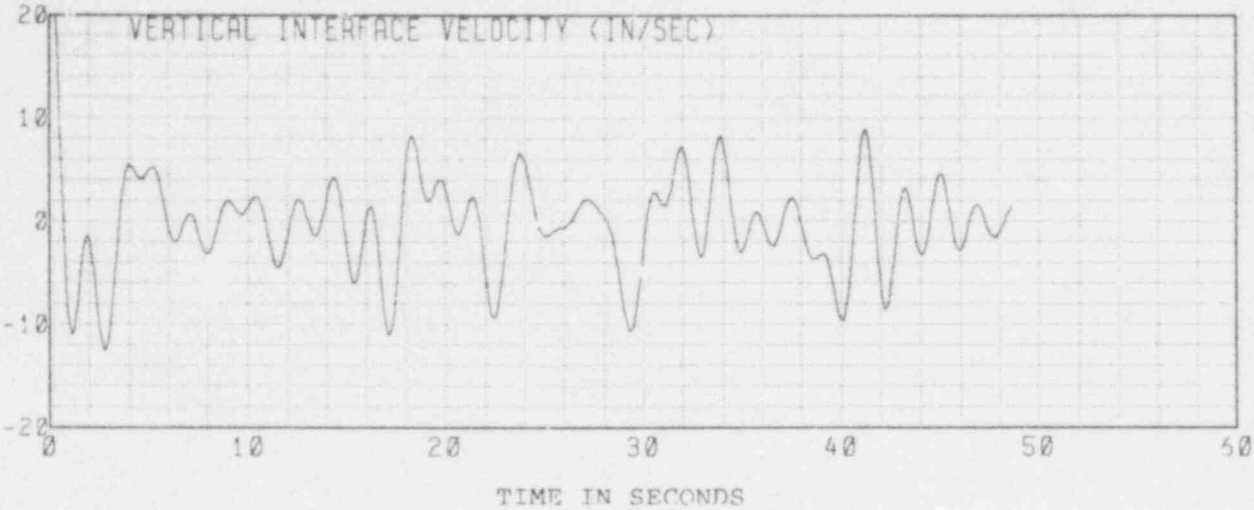


Figure 20. EXAMPLE OF COMPUTED INTERFACE VELOCITY (TEST ST401E)

TABLE 1

VELOCITIES OF MAJOR INTERFACE EXCURSIONS - TEST ST401E

Time	DOWNWARD MOTION		UPWARD MOTION	
	Mean	Peak	Mean	Peak
4	-7.8	-12.6	4.1	5.5
18	-6.3	-11.1	4.1	8.3
23	-6.1	-9.4	4.0	6.7
30	-5.7	-10.7	3.4	7.2
40	-4.7	-9.7	——	——
Averages:	-6.1	-10.7	3.9	6.9

Values in in./sec

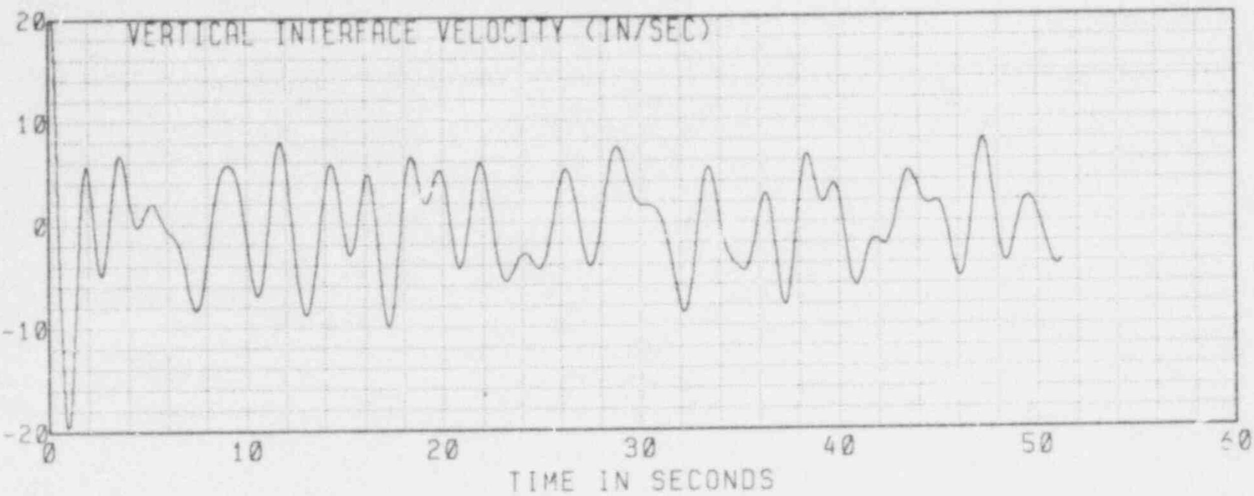


Figure 21. COMPUTED INTERFACE VELOCITY SHOWING REGULAR OSCILLATIONS (TEST ST801E)

TABLE 2

VELOCITY SUMMARY FOR INTERFACE OSCILLATIONS
TEST ST801E

Downward Motion		Upward Motion	
Mean	Peak	Mean	Peak
-3.8	-6.2	3.4	5.7
Average Velocities (in./sec) for 15 Oscillations			

too brief to be significant. These velocities may be compared to the injection velocity, which for this 40 gpm test is approximately 20 in./sec, and the horizontal fluid velocities in the annulus which are on the order of 5-25 in./sec.

For each event shown in Table 1 the downward velocity exceeds the upward by a significant amount. The same is not true of the second example, taken from the 80 gpm test whose filtered interface height curve is shown in Figure 17. During this test the interface motion is more like a semi-regular oscillation than discrete movements. The derivative of this curve, shown in Figure 21, has a more regular appearance than the first example. We will not tabulate the values for the individual peaks; the averages are shown in Table 2. The differences between the upward and downward velocities are not significant. The root mean square velocity through the entire test, which can be thought of as the mean (directionless) speed of the interface, is 4.4 in./sec. These velocities are significantly smaller than the injection velocity (order of 40 in./sec) and the horizontal annulus velocity (10 to 50 in./sec). These global velocities and their dominant oscillation frequencies can also be compared with the results of simple analyses such as those of [3,12] or with advanced code calculations. Codes able to compute fine flow details could be assessed more thoroughly by reducing flow topography data using more elaborate interface algorithms.

4.6 Interface Motion and Pressure Variations

We conclude this discussion of flow topography data analysis methods with an example which correlates motions of the computer-defined phase interface with characteristics of recorded pressure traces. Section 3.4 gave examples of pressure recordings from countercurrent flow tests and pointed out that the pressures are dominated by semi-periodic oscillations at approximately 2 to 3 Hz. These oscillations originate in condensation and momentum transfer interactions between the steam and water in the vessel and their frequencies are typical of those calculated by available analyses. Routines which implement the Fast Fourier Transform can be used to quantitatively examine the frequency distributions of the pressure signals. For example, Figure 22 shows for a sequence of three tests with constant water supply rate and increasing steam supply rate normalized power spectra for recorded differential pressures between the break and the lower plenum. As the figure shows, there is some tendency for the dominant frequency to increase with increasing steam flow. The tests we have performed used highly subcooled water, and the range of steam flow values from full delivery to complete bypass is small. Moreover, the ratio of downcomer liquid mass to compliance of the steam-filled space remains approximately constant in these experiments. Thus, while analysis of the pressure data reveals them to be consistent with models of the fluid dynamic behavior, the pressure data do not strongly challenge those models.

Compared to the pressure oscillations (which arise from local condensation events), large-scale motions of the steam/water interface occur with much lower frequency. At very high steam flows the interface motion sometimes has a semi-periodic appearance, but with periods of several seconds. At steam flows which are more moderate (but still high enough to cause lengthy periods of bypass), the interface frequently remain essentially stationary for several seconds and suddenly move rapidly. These motions are irregular and non-periodic, despite steady-state test conditions with choked steam flow. A series of 10 tests performed with fixed steam and water supply rates confirms this observation. As the resulting data show, plots of interface motion from these tests all have a similar appearance, qualitatively speaking, but the times and magnitudes of the major interface motions are in no way repeatable.

If the rapid pressure oscillations are removed from the gage pressures recorded in the lower plenum and near the break, smaller and slower variations are seen which correspond to interface motions. Figure 23a shows the raw lower plenum gage pressure recorded during the test whose interface height was plotted in Figure 15c. Figure 23b shows the same pressure history with a greatly magnified vertical scale after it has been subjected to a low-pass filter with a cutoff frequency of 0.5 Hz. Positive pressure excursions of about 3 psi, previously hidden by the higher frequency oscillations, occur at approximately 18 and 30 seconds. The filtered interface height curve is repeated in Figure 23c, showing that these are the times of two large downward motions of the liquid mass. The motion of a similar magnitude at 4 seconds corresponds to the initial pressure ramp-down. When the interface reaches the bottom of the annulus and filling commences at 40 seconds, a pair of negative pressure spikes is seen. The reversal of the transient pressure effect signals the alteration of the dominating flow regime. This pattern of events is repeated in Figure 24, which presents filtered pressure and interface data from the test shown previously in Figure 17. Downward interface motions within the annulus correspond to positive pressure excursions; the slug delivery events at 38 and 42 seconds are accompanied by brief periods of negative pressure. In both examples the pressure events tend to slightly precede the corresponding interface motions. This is particularly true of the negative spikes near the times of delivery.

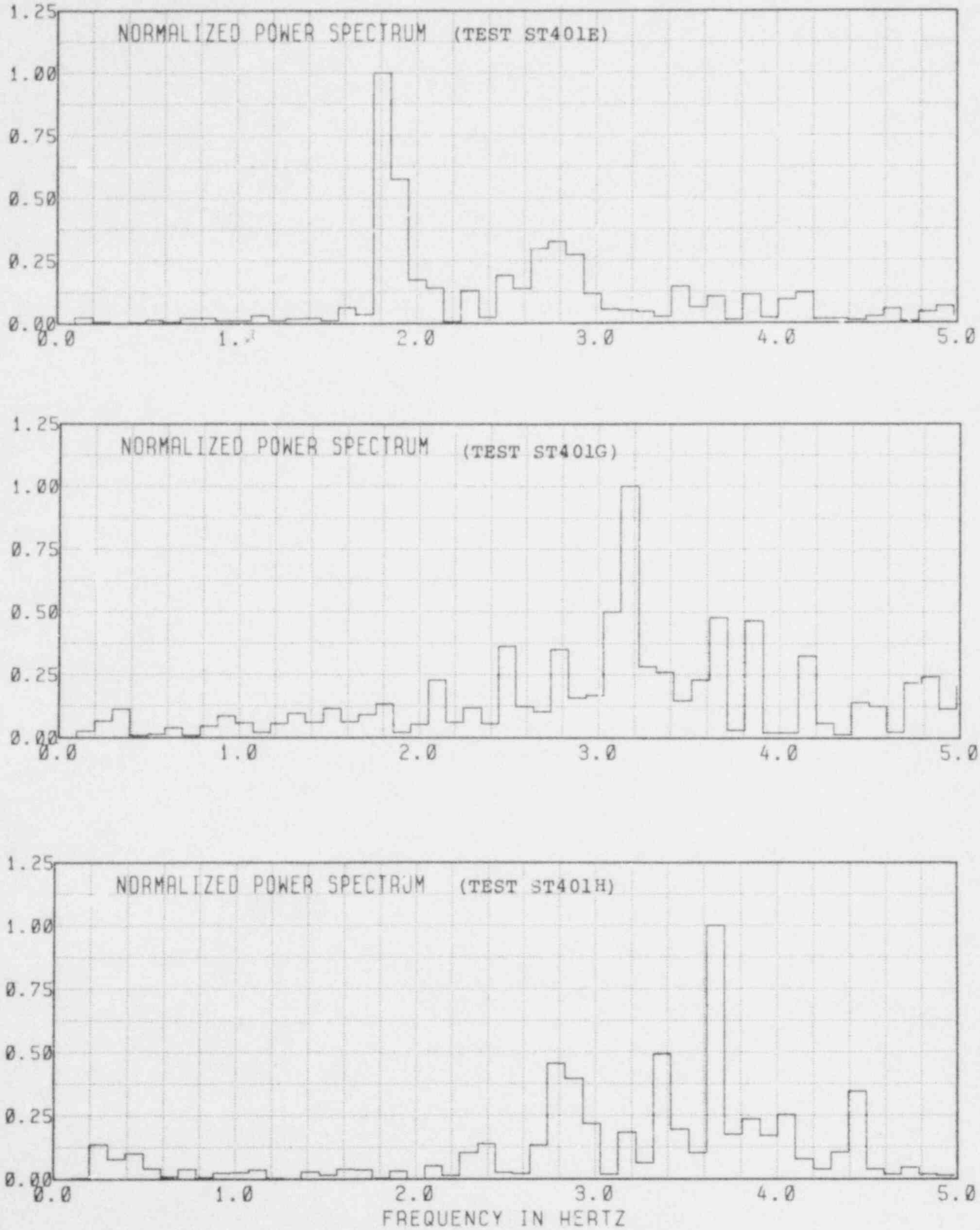
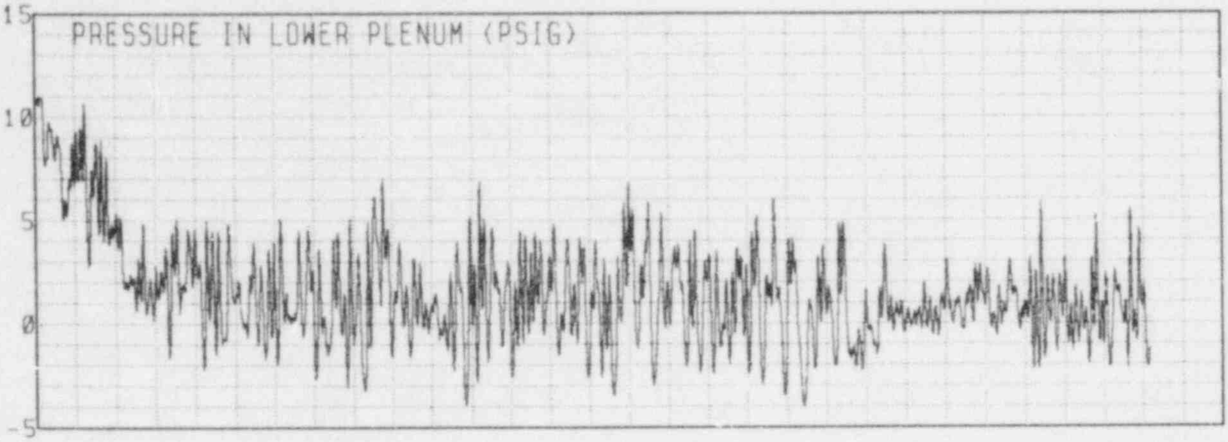
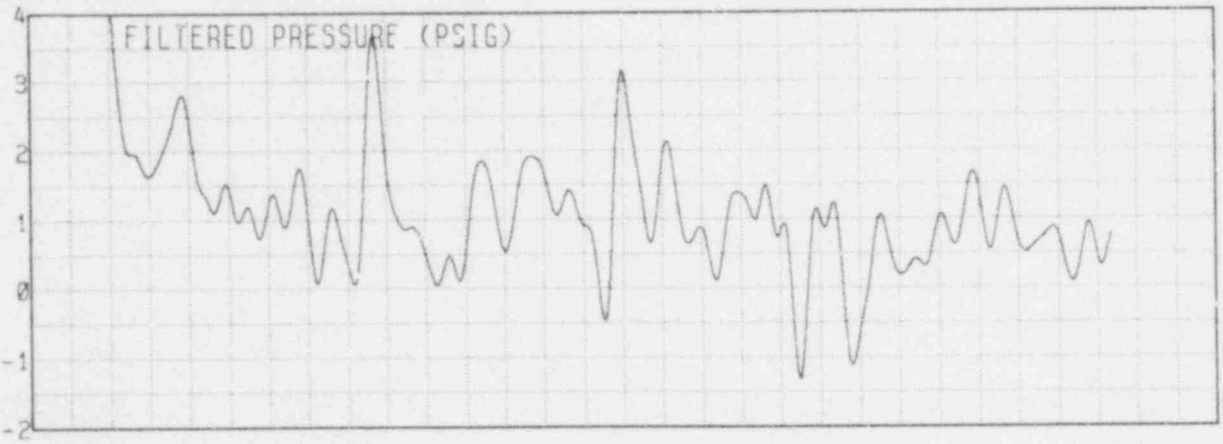


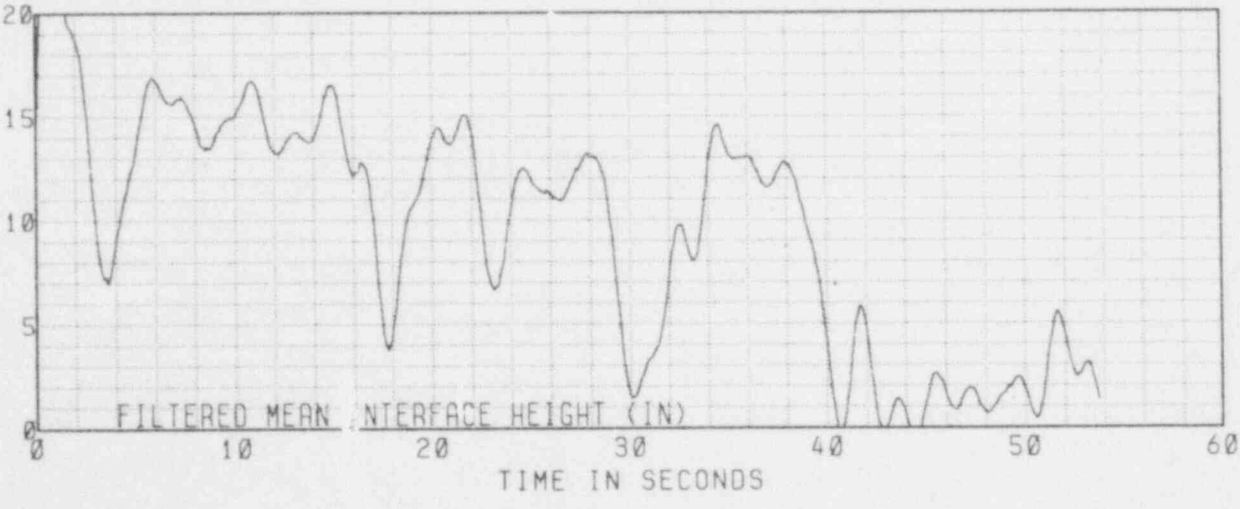
Figure 22. POWER SPECTRAL DISTRIBUTIONS FOR PRESSURE SIGNALS FROM THREE TESTS WITH INCREASING STEAM SUPPLY RATE (TESTS ST401E, ST401G, ST401H)



a) Raw recorded pressure



b) Pressure trace smoothed by low-pass filter (scale magnified)



c) Corresponding filtered interface height

Figure 23. EXAMPLE OF PRESSURE EXCURSIONS CORRESPONDING TO INTERFACE MOTIONS (TEST ST401E)

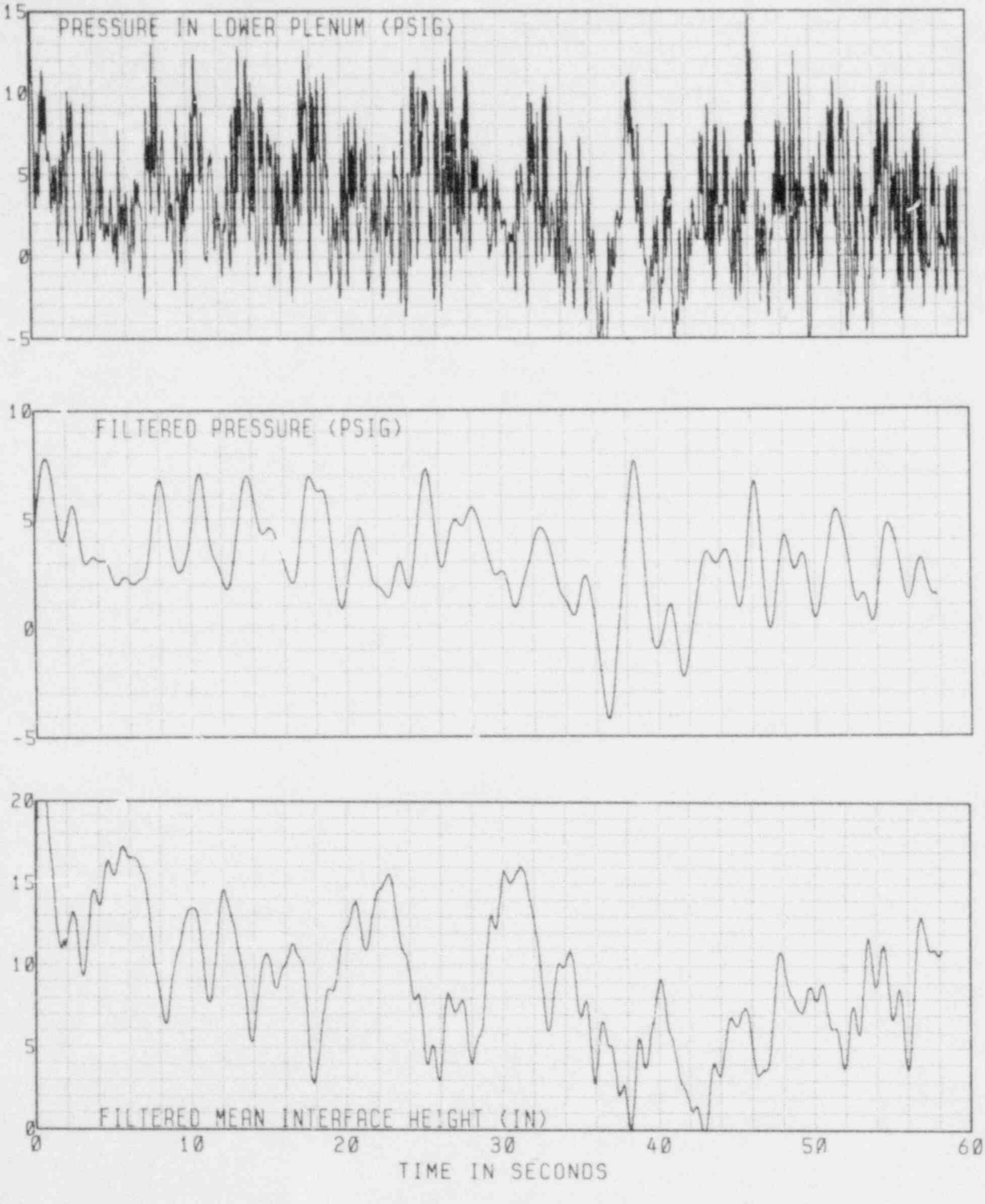


Figure 24. PRESSURE VARIATIONS CORRESPONDING TO OSCILLATORY INTERFACE MOTION AND SLUG DELIVERY

These specific observations provide an example of the use of well-known mathematical techniques to demonstrate a correspondence between quantities derivable from flow topography recordings and independently recorded data (in this case, pressures). It should be straightforward to apply these and other similar methods to develop correlation techniques appropriate for many applications.

5 CONCLUSION

The invention and subsequent development of the flow topography mapping system has provided the fluid dynamics experimentalist with a powerful new tool that promises to find widespread application. It provides a readily usable means for obtaining detailed visual and quantitative information about rapid and complex two-phase flow processes which take place in normally inaccessible regions. Unlike many other recently proposed techniques, it does not rely on highly sophisticated or prohibitvely expensive hardware. Reliable and compact sensors are used with simple electronics and standard computer techniques to provide detailed data from which a variety of local and global flow characteristics may be computed. We will briefly restate some important facts concerning the principal system elements.

Phase Sensors. Creare's demonstration tests have utilized sensors which exploit conductivity differences between the phases. The remainder of the system is insensitive to the particular method used to distinguish the phases and would work equally well with other types of sensors, such as optical probes. It is not difficult to construct small, unobtrusive probes which have minimal effect on flow. Problems which in the past severely limited probe lifetimes have been understood and solved.

Conditioning Electronics. Electronic circuitry associated with the probes is extremely simple, consisting of little more than a resistor. There are no analog signals to be amplified or otherwise conditioned. Circuitry which handles signals from several hundred sensors easily fits within a small rack-mounted enclosure. No tuning or calibration is required. The outputs are simple on/off indications which require no subtle interpretation.

Computer Interface. Standard digital latching and scanning circuits assembled from commercially available parts are used exclusively. Data are transferred to the computer via standard peripheral interface devices. Several hundred sensors can be sampled several hundred times per second without exceeding the data rates readily supported by today's hardware.

Support Computer. Minimal processor power is required for data acquisition and recording. A dedicated microprocessor is sufficient, or a small fraction of the power of a larger time-shared computer will suffice. If desired, data can be recorded using a small laboratory computer with data files being subsequently tranferred to a larger machine for display and analysis.

Software Tools. Creare has implemented and refined basic techniques for determining position and velocity components for phase interfaces. These techniques can readily be modified and adapted to meet the needs of specific applications. The numeric form of the recorded data makes them amenable to the application of a variety of calculations for the purpose of inferring flow characteristics.

Display Devices. Inexpensive video terminals can reproduce topography snapshots in real-time or interactive modes. Computer-driven hard-copy plotters can provide permanent documentation. Data and computed quantities such as phase interfaces suited to specific flow models can be transferred to film to create dynamic and highly graphic recreations of flow processes.

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*Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, DC 20555, and the National Technical Information Service, Springfield, VA 22161.

APPENDIX A

PROBE CHARACTERISTICS

Response Time

Two methods have been used to measure the time required for the conductivity sensors to respond to wetting and unwetting. The first used a probe mounted in a transparent tube with its sensors driving light-emitting diodes. The tube was filled with water and air bubbles were injected from below so that they encountered the sensors as they rose. A high speed movie camera (1000 frames/sec) was used to film the motion of the bubbles and the states of the LED's. A sensor's response time was measured by counting frames from the point at which the phase interface reached the sensor to the point at which its LED responded. The precision of this method is limited by the difficulty in determining the exact location of the interface, but after viewing numerous wetting and unwetting events it is clear that the probe response time is consistently less than 5 ms.

A more precise measurement is described in detail in [6]. A single sensor was mounted on a pressure transducer, and the outputs of the sensor and the transducer were displayed on a dual trace storage oscilloscope. A water droplet was allowed to fall on the sensor and the oscilloscope traces were used to compare the sensor on and off times to the droplet impact time recorded by the pressure transducer. The display permitted resolution of event times to 0.1 ms. A series of tests showed that the response to wetting was too fast to measure and that the response to unwetting was consistently near 1 ms.

Probe Life

The useful lifetime of conductivity probes can be ended either by loss of mechanical integrity due to thermal cycling (cracking or distortion resulting in leakage to the probe interior) or by electrochemical effects which reduce the inherent conductivity of the sensor electrodes. Mechanical integrity depends on a variety of factors unique to each specific probe design: choice of materials, geometry, assembly techniques, etc. The integrity of the probes described in this report has been demonstrated by their use in several dozen countercurrent flow tests involving hundreds or thousands of thermal cycles with no observed failures. Electrochemical degradation can be partially quantified; lower bounds on useful lifetimes of specific probe designs can be determined by extrapolation from observed lifetimes of alternate designs. We have performed tests which show that the lifetimes of properly designed probes will not be limited by electrochemistry.

Lifetime tests were performed on probes of the type described in Section 2 and on an alternate design which differed in two important ways: the electrode material and its exposed surface area. The alternate design used copper electrodes, a metal known to be more electro-active than stainless steel, with surface areas about 1/15 that of the electrodes shown in Figure 3. The latter parameter influences the current flux through the sensor, which is turn has a direct effect on the rate of electrochemical processes. Probes of each type were tested with electrical duty cycles of 1% and 100%. The smaller value is used during normal system operation, and the latter produces a much larger time-averaged current flux. Eighteen sensors of each type were submerged and powered with a 1% duty cycle for 500 hours; no failures were observed. The probes were then operated for an additional 22 hours with a 100% duty cycle. None of the stainless steel sensors failed, but a majority of the copper sensors failed after 6 to 8 hours. At that point their outputs begain to drift erratically between the high and low states.

By direct observation the stainless steel probes have a minimum lifetime of 500 hours while submerged and powered with their normal 1% duty cycle. An estimate of typical true lifetimes can be extrapolated from the observed lifetimes of the continuously powered copper probes. The 1% duty cycle contributes at least a factor of 100, the increased surface area a factor of 15, and the use of stainless steel in place of copper has a beneficial effect of unknown but probably large magnitude. It is probable that probes of this type will operate in excess of 10,000 hours without failing.

APPENDIX B

SUMMARY OF COUNTERCURRENT FLOW TESTS

Test Conditions

Several series of countercurrent flow tests have been performed in the Flow Topography test facility. All tests were performed with fixed water and steam supply rates and used highly subcooled water. Each series (except the last) included steam flow values set at regular intervals to produce results ranging from full delivery to complete bypass. During facility construction and checkout, three series of shakedown tests were performed which recorded data from conductivity probes only; pressures were not recorded. Once the test facility had been checked out in its final configuration, three demonstration test series were run with full instrumentation:

Series ST201 — 12 tests — fluid injected at 20 gpm
Series ST401 — 8 tests — fluid injected at 40 gpm
Series ST801 — 6 tests — fluid injected at 80 gpm

All examples seen in this report and in the film described below are taken from these test series. Finally, two additional series were performed as consistency checks:

Series ST202 — 6 tests — fluid injected at 20 gpm
Series ST40XE — 9 tests — fluid injected at 40 gpm

Series ST202 repeated a full range of steam flows with water injected at 20 gpm. Table B-1 gives steam supply rates and average lower plenum pressures for each test in Series ST201, ST401, ST801, and ST202. Each test in Series ST40XE used the same steam and water supply rates as test ST401E from Series ST401; thus this particular test was performed 10 times altogether. See Section 4.6 for a comment on the results obtained.

All test data files have been preserved at Creare on magnetic tape.

Demonstration Film

During the course of this project several motion picture films have been prepared. Here we describe a documentary film prepared specifically to correspond with the demonstration test data. This film is intended to:

1) Demonstrate the use of the Flow Topography system to create visual reproductions of high-speed flow processes.

2) Document a representative sample of countercurrent flow tests.

3) Demonstrate the performance of the automatic phase interface locating algorithm described in Section 4.3 under a variety of conditions.

Full tests and portions of tests appear in the film at their true speed and at 6X slow motion. To obtain the correct speeds the film should be projected at 18 frames per second; each segment of the film includes a digital timer showing test time which can be used to adjust the projector speed. The film is best viewed with an analyst projector; capability for freeze-frame and very slow projection will aid in viewing details which otherwise may pass too rapidly to be seen clearly.

TABLE B-1

SUMMARY OF DEMONSTRATION TEST CONDITIONS

Test	Series ST201			Series ST401			Series ST801			Series ST202		
	Steam Flow (lbm/sec)	Average LP Pressure (psig)	J^*_{gc}	Steam Flow (lbm/sec)	Average LP Pressure (psig)	J^*_{gc}	Steam Flow (lbm/sec)	Average LP Pressure (psig)	J^*_{gc}	Steam Flow (lbm/sec)	Average LP Pressure (psig)	J^*_{gc}
A	0.0	-0.1	0.0	0.341	0.5	0.147	0.0	0.0	0.0	0.0	-0.1	0.0
B	0.172	0.0	0.075	0.373	1.0	0.158	0.376	-0.1	0.165	0.264	0.1	0.1[illegible]
C	0.229	0.0	0.099	0.43[illegible]	1.5	0.183	0.501	0.0	0.219	0.394	1.3	0.154
D	0.272	0.1	0.118	0.479	2.0	0.197	0.607	1.6	0.253	0.456	2.6	0.183
E	0.327	0.4	0.140	0.520	2.5	0.211	0.701	3.1	0.280	0.509	4.8	0.193
F	0.353	0.8	0.149	0.554	3.0	0.222	0.784	3.1	0.313	0.567	7.4	0.203
G	0.388	1.6	0.160	0.590	3.5	0.233						
H	0.419	2.0	0.171	0.620	4.0	0.242						
I	0.445	2.6	0.179									
J	0.472	3.4	0.185									
K	0.520	5.8	0.192									
L	0.585	10.7	0.195									

Water Temperature for All Tests: 55°F

Examples are included from tests recorded with each of three fluid injection rates, 20, 40, and 80 gpm. Tests recorded at 20 gpm have an appearance that is qualitatively different from those at 40 and 80 gpm. As examples in the report and in the film show, tests at 40 and 80 gpm with high steam flows exhibit lengthy periods of complete bypass, during which the steam/water interface never reaches the bottom of the annulus. In contrast, during 20 gpm tests the interface moves rapidly to the bottom of the annulus following injection, regardless of the level of reverse steam flow. The rate of plenum filling diminishes as the steam flow is increased, but one does not see the entire lower portion of the annulus become cleared of fluid as in the tests with higher water injection rates.

In some portions of the film, the computer-generated interface line sometimes appears briefly near the top of an annulus which is mostly filled with fluid. This occurs during periods of delivery when the only part of the annulus not filled with fluid is the part above the inlets. The algorithm was modified to suppress these solutions, and they do not appear in the more recently generated segments of the film (not necessarily those nearest the end).

Summary of Tests Seen in Film

Fluid injected at 20 gpm:

Test ST201G — Moderate steam flow. The lower plenum fills at approximately 15 gpm. The test lasts 45 seconds and is shown at its true speed. Delivery is continuous, but portions of the annulus are frequently and briefly cleared of fluid. The phase interface appears to "dance" about in the lower annulus.

Test ST201K — Higher steam flow. After 70 seconds the lower plenum is less than half full. The appearance of the data and interface solutions is similar to that of the previous test. A portion of this test is repeated in slow motion.

Fluid injected at 40 gpm:

Test ST401D — Moderate steam flow. After an initial period of bypass lasting 15 seconds, the lower plenum fills at the injection rate. The first half of the test is repeated in slow motion.

Test ST401E — Higher steam flow. Initial bypyass lasts for 40 seconds, followed by filling at the injection rate. A 20-second period from the center of the test is repeated in slow motion.

Test ST401H — Much higher steam flow. The test lasts 50 seconds, but there is no delivery. At several times, however, the annulus appears to be nearly full.

Fluid injected at 80 gpm:

Test ST801D — Moderate steam flow. The lower plenum is filled by a series of slug deliveries during a 10-second period.

Test ST801E — Higher steam flow. All fluid is bypassed except for two brief but large slug deliveries near 40 seconds. A portion of the test including the slug deliveries is repeated in slow motion.

Test ST801F — Very high steam flow. No fluid is delivered, and in fact, it seldom reaches the lower half of the annulus.

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1. REPORT NUMBER *(Assigned by DDC)* NUREG/CR-1333 TN-314	
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7. AUTHOR(S) Clifford N. Cary	5. DATE REPORT COMPLETED MONTH January YEAR 1980
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16. ABSTRACT *(200 words or less)*

An instrumentation system has been developed and used to record, display and analyze two-phase flow topographies. This report describes the devices designed; the computer analysis techniques used to derive two-phase flow distributions, velocities, and interfaces; and the application and demonstration of these techniques during experiments in a model reactor vessel. These techniques have broad instrumentation applicability.

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17b. IDENTIFIERS/OPEN-ENDED TERMS

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