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DEFICIENT COOLING
FOURTH QUARTERLY PROGRESS REPORT
APRIL 1-JUNE 30, 1970

U.S. ATOMIC ENERGY COMMISSION
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DEFICIENT COOLING

FOURTH QUARTERLY PROGRESS REPORT

April 1—June 30, 1970

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SUMMARY

A simplified analysis of boiling two-phase transients, involving pressure and/or flow decay has been made using the method of characteristics. The results appear encouraging for analysis of transient data and work is presently in progress on evaluation of representative transient depressurization data.

Procurement of materials for subchannel sampling of three areas of a nine-rod test section have been completed and installation started. Completion of the installation will be made early in the next quarter (July 1970).

One-rod exploratory tests have revealed poor heat transfer conditions around supports of large (1/4 inch) diameter in contact with the heater surface.

Flow cycling tests have proved the adequacy of the designed equipment and have also shown that CHF is indicated to be sensitive to changes in quality of 0.005 at 1000 psi.

The analog-digital conversion routine and programming for calculation of transient data is essentially complete. Some minor de-bugging is still in progress.

1. INTRODUCTION

1.1 GENERAL

The work on the Deficient Cooling Program is directed toward extension of out-of-pile heat transfer data in support of current nuclear-powered, water-cooled plants. A brief review of current technology reveals that the large bulk of data is of the steady- or quasi-steady-state class. Thus, a need exists for data taken under transient conditions of power, flow and pressure in combination with different geometries. Analysis and study of such data are expected to contribute to the following overall objectives:

- a. A firmer understanding and establishment of heat transfer safety limitations, and
- b. Extension of safe operating limits to higher power densities.

Deficient cooling conditions are considered to be those which result in inadequate cooling of the fuel. They may result in potentially excessive cladding temperature which, in combination with the internal gas pressure of the fuel, may cause some type of fuel disruption. Resultant temperatures depend on the mode or modes of heat transfer that arise during deficient cooling conditions. A brief description of these modes of heat transfer follows.

Three different modes of heat transfer can generally occur when heat is removed, during high quality conditions, from a surface such as a fuel rod: nucleate boiling, with a liquid film on the heated surface; transition boiling; and the liquid deficient region. Nucleate boiling occurs at very high surface heat transfer coefficients, usually in excess of 10,000 Btu/h-ft², with steady surface temperatures. Increase of heat flux eventually results in "film dryout" and a change of mode to transition boiling, which is usually characterized by temperature oscillations of varying amplitude on the heated surface. The transition mode of heat transfer exhibits relatively low heat transfer coefficients, on the order of 1000 Btu/h-ft² or less. Continued increase of heat flux eventually results in the liquid deficient regions, with some liquid droplets impinging on the heated surface which is mostly steam cooled.

The heat flux at which transition is made from the nucleate to transition mode of boiling, as evidenced by onset of surface temperature oscillations, is usually termed the critical heat flux (CHF). For low qualities, it is also known as the

departure from nucleate boiling (DNB), or burnout point. Considerable effort has been made on parametric definition of the CHF with pressure, coolant flow, vapor quality, and the geometry of the system. These parametric studies serve as design data and indicate the operating conditions beyond which fuel surface temperatures increase substantially, with greater risk to fuel cladding integrity.

Most of the work defining limits of CHF has been done with small incremental heat flux increases which would allow it to be classified as quasi-steady-state data. However, the actual modes of heat transfer become more complex in some cases involving transients, when the dynamic characteristics of the fuel-coolant system come into play. Therefore practical cases of transient conditions which are considered worthwhile for study and test under this Deficient Cooling Program are those involving:

- a. Transient reduction of flow,
- b. Transient increase of power,
- c. Oscillation of power into and out of the transition boiling region to determine effects of prolonged operation at CHF, and
- d. Transient decrease of pressure which causes flashing and potentially deficient cooling conditions due to increased void content.

Furthermore, it is proposed to study under transient conditions typical geometry changes such as those due to fuel spacer components and those caused by rod blowing and swelling. Such studies are expected to define more clearly heat transfer safety limitations, and will eventually result in extension of safe operation to higher limits.

1.2 PROGRAM OBJECTIVES

The objectives expected to be accomplished under this program are as follows:

- a. Determine experimentally the CHF and temperature regimes which may occur in water reactor fuel assemblies due to nonstandard cooling conditions that result from power, flow, or pressure transients, and determine these values relative to steady-state data.
- b. Evaluate temperature regimes likely to be experienced by water reactor fuel assemblies in loss-of-coolant accidents, and determine areas of similarity or relationship between these regimes and those found in transient critical conditions.
- c. Evaluate consequences of fuel rod geometry changes on heat transfer performance from simulated tests on single, electrically-heated rods.
- d. Provide a plan for further in- and out-of-pile work necessary for more complete performance and definition of the performance of water reactor fuel under deficient cooling conditions.

1.3 ORGANIZATION OF PROGRAM

The outline of tasks, as originally proposed for the entire program, is shown in Table 1 with brief reference to the equipment and type of tests. It is intended to preserve these task reference designations in this and subsequent reports so that documenting of work and progress can be made in a systematic manner.

Tasks 3, 4, 5, and 8 involve test work. Chronological sequence of testing will probably proceed in the numerical task order.

Table 1
TASK DESIGNATION AND CONTENT

No.	Title	Content
1	Planning and Analysis	a. Review current technology and plan appropriate tests to integrate with required safety programs b. Analysis as necessary to determine test parameters
2a	Design	a. Design new equipment or modifications of existing equipment to carry out test plans
2b	Manufacture	a. Manufacture or purchase new equipment required
3	One-Rod Exploratory Transient CHF Tests	Exploratory tests involving a. Steady-state and transient flow, power, and pressure b. Cycling of power and flow into the region of CHF transition boiling c. Prolonged exposure to CHF conditions d. Modifications of heaters for nonuniform axial heat flux
4	Multirod Transient Tests	Tests involving: a. Steady state and transient conditions b. Power and flow cycling c. Combinations of intra-bundle clearance, power distribution, and spacer components with a. and b.
5	One-Rod Tests with Geometry Changes	a. Effects of temperature and internal pressure on heater swelling b. Steady-state simulated swelling at constant coolant pressure drop
6	Data Reduction and Analysis	a. As required for test Tasks 1, 3, 4, 5, and 8
7	Project Administration, Reporting, and Recommendations	a. Administration of entire program

Table 1 (Continued)

No.	Title	Content
		b. Regular and topical reporting
		c. Future recommendations for continued efforts
8	Multirod Geometry Changes	a. Steady-state CHF data with spacer components and simulated fuel rod bowing and swelling

2. ANALYSIS (TASK 1)

2.1 TRANSIENT ANALYSIS

In order to be able to understand and predict the thermal-hydraulic behavior of a heated rod-bundle during transient conditions of flow and system pressure, it is essential that one be able to predict the flow rate and enthalpy at any axial position for every point in time during the transient. The complete numerical solution of this problem can be accomplished with large existing computer codes, however, these codes are rather expensive to run and tend to obscure the basic phenomena involved due to their complexity.

In order to gain insight into the transient phenomena a simplified analysis has been performed. The salient assumptions which have been made in this study are:

- 1) No slip (i.e., homogeneous flow),
- 2) Neglect the effect of axial pressure drop compared to the system pressure on thermo-dynamic properties,
- 3) Constant heat flux (i.e., neglect the thermal inertia effects of the heater,
- 4) Neglect kinetic and potential energy terms in the energy equation.

These assumptions have been motivated by more detailed transient solutions using the APED SCAT code.

With these constraints it can be shown that the two-phase energy equation becomes:

$$\rho \frac{Dh}{Dt} = q'' \left(\frac{P_H}{A_{x-s}} \right) + \frac{DP}{Dt} \quad (2-1)$$

in which,

$$\rho \frac{D()}{Dt} \triangleq \rho \frac{\partial ()}{\partial t} + G \frac{\partial ()}{\partial Z}, \text{ (Material derivative)}$$

$$q'' = \text{Heat flux} \left(\frac{\text{BTU}}{\text{Hr-ft}^2} \right)$$

$$\rho \triangleq \frac{1}{[v_f + x v_{fg}]}, \text{ (Homogeneous density, lb/ft}^3\text{)}$$

$P \triangleq$ System pressure (psf)

$G \triangleq$ Mass flux (lb/hr-ft²)

$\chi \triangleq$ Quality

$P_H \triangleq$ Heated parameter (ft)

$A_{x-s} \triangleq$ Area of the cross section (ft²)

$h \triangleq h_f + \chi h_{fg}$, enthalpy

Equation (2-1) can be integrated along the particle path by the "Method of Characteristics".¹ The characteristic equation itself is given by,

$$\frac{DZ}{Dt} = \left(\frac{G}{\rho} \right)_{IN} + \frac{1}{A_{x-s}} \frac{D(m_o/\rho)}{Dt} \quad (2-2)$$

where

$m_o \triangleq$ initial mass in Lagrangian control volume under consideration

The first term on the right hand side of equation (2-2) represents the velocity of the downstream boundary (i.e., inlet) of the control volume while the second term represents the rate of expansion due to boiling in the control volume.

The essence of the solution is that equation (2-1) can always be integrated along the characteristics to yield,

$$\chi = \chi(\chi_o, t) \quad (2-3)$$

where

$\chi_o =$ Initial quality.

Equation (2-2) is then integrated (if possible) to yield,

$$Z = Z(Z_o, t) \quad (2-4)$$

where

Z_o is the initial position of the control volume under consideration. Z_o and χ_o are simply related by a heat balance, hence by combining equations (2-3) and (2-4) one has the solution function of interest,

$$\chi = \chi(Z, t). \quad (2-5)$$

The transient mass flux is then given as

$$G(Z, t) = \rho [\chi(Z, t)] \frac{DZ}{Dt} \quad (2-6)$$

where

Equation (2-2) is used for (DZ/Dt)

An exact analytical solution has been achieved for the case of constant system pressure and an exponential flow decay of the form,

$$G(t)_{IN} = G_0 e^{-t/\tau}, \quad (2-7)$$

Figure 2-1 is a plot of a flow decay case in which $\tau = 3.0$ sec. There was a 6 foot heated length with uniform axial heat flux, and there were saturated conditions at the heater inlet. It can be seen that at the exit ($Z = 6$ ft) and at 2 feet from the exit ($Z = 4$ ft) the quality increases with time after a short "dead band." This initial delay is due to the fact that the mass flux in the two-phase region lags the impressed inlet flow decay since the control volume expansion term (due to boiling) is much stronger than the inlet velocity term. This lag is seen in Figure 2-2, in which the impressed inlet ($Z = 0$ ft) and calculated exit ($Z = 6$ ft) mass flux are compared at each point in time.

In general, it is not possible to integrate equation (2-2) exactly for the depressurization or the combined flow decay and depressurization cases. Nevertheless, this equation can be integrated numerically using the "method of characteristics." Work is currently underway to evaluate representative depressurization transients and to predict the occurrence of CHF data taken in a single rod annulus. Significant results from this work will be reported as they become available.

3. DESIGN AND MANUFACTURE (TASKS 2a, 2b)

3.1 DESIGN AND MANUFACTURE

One indirect heater, made by the Watlow Electric Manufacturing Company, was received and tried in the one-rod test design shown in the first quarterly report, GEAP-13048. An electrical short at the bottom of the test section caused irreparable damage to the rod. Consequently a direct resistance heater and liner were designed and procured so testing could be continued. Details of the test section and instrumentation are shown in Figure 4-1 in the following section.

Design of the nine-rod subchannel sampling system, described in the third quarterly report—GEAP-10196, was completed. Procurement of materials was completed as well as bidding procedures for installation. Work was started in June and will be completed early in the next quarter.

4. EXPERIMENTAL WORK

4.1 ONE-ROD EXPLORATORY TESTS (TASK 3)

4.1.1 Flow Oscillation

Several flow oscillation runs were made with the flow cycling equipment, described in the second quarterly report GEAP-10164, to test its adequacy of operation. The test section used was that shown schematically on Figure 4-1. The equipment operated satisfactorily and a typical result of the exploratory runs is shown on Figure 4-2. CHF was found to be very sensitive to the flow quality.

Power was gradually increased by small steps until a positive CHF was obtained on thermocouple No. 8 with the flow set at the lower value. This is shown on the left side of Figure 4-2. Flow cycling was then started at a period of approximately 20 seconds. Cycling to the higher flow, with power held constant, suppressed CHF for about 35 seconds, after which incipient CHF appeared. The maximum temperature obtained, after initiation of CHF at the low flow portion of the cycle, increased with each successive cycle on both thermocouples 6 and 8. After 11 cycles the temperature on thermocouple 8 reached 850°F and cycling was stopped and power decreased to avoid excessive temperatures.

Figure 2-1. Quality Versus Time at Different Axial Positions

Figure 2-2. Variations of Mass Velocity with Time at Different Axial Positions

Figure 4-1. Thermocouple and Support Arrangement for One-Rod Heater

Figure 4-2. Critical Heat Flux with Oscillating Flow (Run 1-79-2)

Thermocouples 6 and 8, located directly under and one inch before a ball support (Figure 4-2) respectively, were the only thermocouples which showed CHF conditions. Thus CHF conditions were obtained 12-3/8 and 20-3/8 before the end of the heated length (Figure 4-2). This is attributed to the influence of the ball supports on the flow and heat transfer conditions at those locations.

It is of interest to note that heater temperature at thermocouple 8, one inch upstream of a ball, was as much as 100°F higher than at thermocouple 6 directly under a ball. This result is anomalous as thermocouple 8 is located under a region of higher mass velocity, than thermocouple 6 (compare Figures 4-1 and 4-4), and would be expected to be cooler. The result is not consistent, as other runs at similar conditions still under reduction, show thermocouple 6 higher than 8 as would be expected.

Conditions during run 1-79-2, shown on Figure 4-2, are given below.

		Time (Figure 4-2)	
		<u>1735:50</u>	<u>1738:53</u>
Pressure, psi	1000		
Heat Flux, Btu/h-ft ²	646,000		
G, lb/h-ft ² 10 ⁶	1.33		
	1.84		
w, lb/sec	0.72		
	1.00		
 Δh, Subcooling, Btu/lb		109	104
χ, Exit Steam Quality (Based on steady state)	High Flow	0.182	0.19
	Low Flow	0.318	0.326
V, ft/sec (Based on liquid flow)	High Flow	7.6	7.6
	Low Flow	3.8	3.8

The residence time in the test section based on liquid flow is conservatively less than the cycling time at either flow, so the steady state qualities are indicative of the actual conditions at the low and high flows.

The data over the first half of the total run time indicate that incipient CHF at the two thermocouples is quite sensitive to the steam quality. Power was kept constant and the increasing temperatures are due to a gradual decrease in subcooling. This decrease is due to less system inlet losses at the higher flow. Thus, during the first half of the run when CHF conditions developed, the quality change at the lower flow is estimated at only 0.005. The gross effect indicates a high sensitivity to quality. However, additional effects to be considered are the change in the heat transfer coefficient at the heater surface and the flow transient. The latter effect is considered small, as the temperature traces indicate temperatures returned to within a few degrees of the same value at the high flow.

The assembly described above was operated at several film boiling conditions at 1000 psi; mass velocities in the range of $0.5 - 2.2 \times 10^6$ lb/h-ft²; steam qualities of 0.27 - 0.55; and heater temperatures up to 1000°F. Resistivity of the demineralized water was about 300,000 ohm-cm. Figures 4-3 and 4-4 show the flow patterns, around the 1/4 inch balls supporting the rod, caused by heating to 1000°F. These flow patterns were observed in the last 30 inches of the heater's length. Figure 4-4 shows a slight white mineral deposit that necks down between ball supports and outlines the wake downstream of a ball. The black and light area, directly under a ball, indicates areas of highest temperature.

Figure 4-3. Flow Patterns around One-Rod Ball Supports

Figure 4-4. Flow Pattern around One-Rod Ball Support (Assembly 12)

4.1.2 Film Boiling

As described above, the 1/4 inch sapphire heater supports caused poorer heat transfer in their vicinity. The surface temperatures there indicated transition and film boiling before any CHF was observed at the exit end of the heater where there were no balls (CHF thermocouples 1,2,3 on Figure 4-1). Therefore, about thirty data points were taken at various surface temperatures up to 1000°F for calculation of heat transfer coefficients. This data is expected to be ready for presentation in the next quarterly report.

Data was taken at 1000 psi with mass velocities from $0.25 - 2 \times 10^6$ lb/h-ft², and steam quality from about 0.25 - 0.60.

4.2 TRANSIENT FLOW CONTROL VALVE

The flow valve control system, first tried for a transient flow heat transfer test, is described in the second quarterly report, GEAP-10164. The system has two separate pneumatic adjustments which in effect allow initial settings of two different flows at two different valve positions. A switch provides the means of switching from one valve position to the other. This type of control works fine, with a two-phase load such as a boiling test section, provided conditions at each end of the transient allow steady *favorable* operation for setting valve controls. For example, let it be desired to perform a transient flow test between points 1 and 2 on Figure 4-5. The flow is set at each of the end points, 1 and 2, with constant power and inlet water temperature to the boiling test section. The transient may then be performed, from 1 to 2, or 2 to 1 if desired by appropriate operation of the valve control switch.

If a CHF condition exists along the desired transient, say at (3) on Figure 4-5, then setting the valve controls at position 2 may be very unfavorable due to high heater temperatures that can be experienced in transition or film boiling. This is particularly undesirable when the test section contains many heaters and much instrumentation whose costs are extremely high.

During transient tests, with the one-rod heater, it became apparent that the 2-position valve control was not adequate for the ranges of testing desired. Occasionally CHF conditions would lie on the transient path and it was not feasible to hold the test at high temperatures in order to set the low flow valve position. Further, the 2-position controls were not desirable for runs where it was desired to repeat a given flow transient. Therefore, it was decided to try a valve control based on a feed-back loop in which the turbine flow meter (Potter) controlled the extremities of the desired transient. Such a system is expected to provide any desired flow transient, within its range, regardless of the conditions along the transient in the boiling test section. If unfavorable conditions should arise during the transient, contact switches on the heater temperature recorders can be set to trip power at the permissible maximum.

The flow feed-back control system chosen is shown schematically on Figure 4-6. Equipment added, to that already existing, is the General Electric GEMAC controller and Conoflow current-pressure transducer. Open feed-back loop tests, with a pulse to the GEMAC controller, have shown that the valve can travel full stroke in 600 ms. This should be adequate for tests in this program where changes in valve position of about 1/3 stroke are anticipated.

Recent tests with the feed-back circuit closed and flow in the system, at ambient conditions, have revealed some difficulties that must be corrected. The present pneumatic control system has a time lag of 150-200 ms between the instrument air pressure signal and the air pressure supply to the valve stem's piston. This has caused oscillations in the valve position, when a high gain is used to obtain the fast travel desired. At speeds where oscillations are not present, the valve travel is excessively slow. This problem is presently under consideration with the valve supplier.

Figure 4-5. Two-Phase Flow Control Schematic

Figure 4-6. Flow Control Feedback Circuit

5. DATA RECORDING AND REDUCTION

5.1 ANALOG-DIGITAL CONVERSION

The analog to digital (A/D) conversion involves sampling test data recorded on an analog tape at discrete time intervals and recording these samples in binary form on a magnetic tape. The analog tape has a maximum of fourteen channels with a different test parameter recorded on each channel. The A/D conversion equipment uses a multiplexing system to read each channel on the analog tape with a 25 microsecond delay between readings. After sampling all channels, the system waits a specified time interval and again samples each channel. The time lapse of 25 microseconds between channel samplings is considered negligible, compared to the sampling time and the rates of change in test parameters, so that all channels are assumed to be sampled at the same instant in time.

The data must be recorded on the digital tape in a binary form that is compatible with the GE 635 computer. To insure compatibility, the following items were specified for the digital tape:

- a. Fixed word length of 36 bits
- b. Fixed record length of up to 320 words
- c. Fixed block length of up to 320 words
- d. Density of 800 bits per inch
- e. No binary labels on tape.

The 36 bit word format chosen (shown in Figure 5-1) contains an eleven bit data field, a twenty four bit time field and a sign bit. The eleven bit data field allows an integer output range of 0 to 2048 to be stored in this field. The twenty four bits in the time field must be filled with zeros. The sign bit is on for the analog channel number one only and left off for the other channels. This makes it possible to identify the channels when recorded on the digital tape.

Selection of the sampling time interval is based on the speed of the transient test parameters and on minimization of frequency aliasing error. The magnitude of the time lag introduced by the flow measuring instrumentation also has a bearing

6	1	7	13	19	x
5	11	6	12	18	24
4	10	5	11	17	23
3	9	4	10	16	22
2	8	3	9	15	21
1	7	2	8	14	20

DATA TIME

x = SIGN BIT

Figure 5-1. Word Format for Digital Tape

on selection of the sample interval. This is further discussed in the section of this report on lag correction. Frequency aliasing error occurs when frequencies in the data, which are higher than half the sampling frequency f_s , are *folded* into the lower frequency range from 0 to $1/2 f_s$ and confused with data in this lower range.

The most practical method of handling this type of error is to filter the data during the A/D conversion prior to sampling so that information above a maximum desired cutoff frequency is no longer contained in the data. This filtered data can then be sampled at twice the filter cutoff frequency to give accurate results. The highest frequency of interest in test data has been in transient flow CHF tests. These flow transients were exponential decays with a minimum time constant of 0.1 seconds which corresponds to a maximum frequency of interest of 10 radians/sec. A conservative filter cutoff frequency of 20 to 25 cps was used in the A/D conversion of this data with a minimum sampling rate of 40 samples/sec.

5.2 COMPUTER CODE FOR READING DIGITAL TAPE AND REDUCING TEST DATA

A computer code called TAPER has been developed to read the digital tape on the GE 635 computer. Included in the code is a subroutine for data reduction. A logic flow diagram of this program is shown in Figure 5-2.

The program begins by reading one fixed length record from the tape and temporarily storing it in a two dimensional array called RECORD. The rows of this array correspond to the channels of the analog tape. Although the channel data is stored in each record in the same order as the channel numbers, the channel numbers may not necessarily correspond to the row numbers in which the data is stored (i.e., channel one data may be stored in row three, channel two in row four, etc.). In order to indicate which row corresponds to channel one, a one is stored in the sign bit of that row during the A/D conversion. After the first record is read, the program finds the row of the RECORD array that has the one in the sign bit. The one in the sign bit is then removed from that row in each record after it has been read from the tape. Retention of the one would cause the values stored in that row to be read as negative numbers.

After reading the first record and finding the location of channel one, a loop is begun in which a new record is read from the tape each time through the loop. Each new record is temporarily saved in the RECORD array, the one is removed from the sign bit, and the record is then stored in the CHAN array. During this transfer, the rows of RECORD are reordered, if necessary, so that data from each original analog channel is stored in the corresponding row of the CHAN array. In order to conserve on core requirements, only a specified number of records are saved in the CHAN array at any one time. As a new record is stored in this array, the "oldest" record in the array is dropped from memory.

The output scale of the A/D conversion equipment is 0 to 2048 corresponding to an input scale from the analog tape of +500 to -500 millivolts. Thus the values stored in each record must be converted back to the magnitudes of the input scale. After this has been done in a newly read record, the program scans the marker channel of that record for the beginning of a marker which indicates the location of a particular test run. This marker is a step increase in d-c voltage which is applied to the marker channel input at the beginning of the test run and kept on until the end of the run. If no marker is found in that record, the loop is continued and the next record is read.

When the beginning of a run is found, the loop continues to read new records and stores the test data in a new array until the end of the marker is found. A subroutine for reducing the test data is then called. This subroutine converts the test data recorded in millivolts to engineering units using calibration curves for the test instrumentation. Included in the subroutine is a correction for a first order electronic lag caused by the frequency converter of the turbine flow meter system. Also included is a numerical filter for smoothing the flow data. The lag correction and numerical filter are discussed further in paragraphs 5.2.1 and 5.2.2. After completing the necessary calculations, the subroutine then prints out the reduced test data for that particular run and returns control to the loop in the main program. The program then continues to read records from the tape and searches for the remaining test runs. When the last run has been found or an end of file mark is read from the tape, the program is stopped.

5.2.1 Correction for Time Lag in Turbine Meter Flow Readings

The time lag encountered in the flow data is caused by the low pass filter characteristics of the turbine meter frequency converter. Figure 5-3 represents the system to be considered. The continuous signal, $x(t)$, from the turbine meter is input to the frequency converter with lag characteristics represented by the transfer function, $h(t)$. The continuous output of the frequency converter is then sampled at equally spaced intervals in time, T , to give the sampled output, $y^*(t)$.

It has been shown experimentally that the transfer function, $h(t)$, is a simple, first order lag with unity gain:

$$h(t) = \frac{1}{\tau} e^{-t/\tau} \quad (5-1)$$

In Laplace space, this transfer function is

$$H(s) = \frac{1}{\tau s + 1} \quad (5-2)$$

where

τ = time constant of system

The sampled output, $y^*(t)$, from the turbine meter is recorded during each transient CHF test. In order to determine the actual flow, $x(t)$, the output must be corrected for the time lag resulting from the transfer function, $h(t)$. The method used to make this correction employs sampled data theory.

The continuous system in Figure 5-3 is represented by the sampled data system shown in Figure 5-4. This system samples the continuous input signal $x(s)$, at equally spaced time intervals, T .

The zero order data hold operator (see Appendix A for derivation of data hold operator) reconstructs the continuous input with a series of step approximations as shown in Figure 5-5. The system transfer function, $H(s)$, operates on the reconstructed continuous input, $\tilde{x}(s)$, to give the continuous output, $\tilde{y}(s)$, which is then sampled at equally spaced intervals, T . This model differs from the actual system in the following respect. The actual system operates on the original continuous signal without the initial sampling and data hold as shown in Figure 5-4. By introducing the sampler and data hold operator into the system model, the sampled input can be predicted from the recorded sample output, using existing sample data techniques².

Another type of data hold operator for reconstruction of the continuous input uses a polygonal approximation to the continuous signal instead of the step approximation as shown in Figure 5-5. This type of data hold operator is more accurate than the zero-order hold operator in many cases but was found to be extremely inaccurate on test cases where the output, $y(t)$, was an exponential decay. Since an exponential decay is typical of many of the flow transient tests to be conducted, this type of data hold operator was not used.

Using the sampled data model, the following recursion relationship can be derived (see Appendix A) for the corrected sampled input as a function of the sampled output.

Figure 5-2. Logic Flow Diagram of TAPER

$x(t)$ = CONTINUOUS INPUT
 $h(t)$ = SYSTEM TRANSFER FUNCTION
 T = SAMPLE INTERVAL
 $y(t)$ = SAMPLED OUTPUT

Figure 5-3. Representation of System

$x(s)$ = CONTINUOUS INPUT
 $x^*(s)$ = SAMPLED INPUT
 $\tilde{x}(s)$ = RECONSTRUCTED CONTINUOUS INPUT
 $\tilde{Y}(s)$ = CONTINUOUS OUTPUT OF SYSTEM
 $Y^*(s)$ = SAMPLED OUTPUT
 Ts = SAMPLE INTERVAL
 $\frac{1 - e^{-Ts}}{s}$ = TRANSFER FUNCTION FOR ZERO ORDER DATA HOLD
 $H(s)$ = SYSTEM TRANSFER FUNCTION

Figure 5-4. Sampled Data Model of System in Laplace Space

Figure 5-5. Reconstruction of $x(t)$ with a Zero-Order Data Hold Operator

$$x_n = \frac{1}{(1 - e^{-T/\tau})} \left[y_{n+1} - e^{-T/\tau} y_n \right] \quad (5-3)$$

where

x_n = input at time nT

y_n, y_{n+1} = output at time $nT, (n+1)T$

T = sampling time interval

τ = time constant of system

The accuracy of the above expression is largely dependent on the sample time interval used. The step approximation of the continuous input as shown in Figure 5-5 becomes more accurate with smaller sample intervals. In addition, the sample interval must be small compared to the time constant of the system lag. These factors as well as frequency aliasing must be considered when selecting the sampling frequency used in the A/D conversion. The time constant of the turbine meter frequency converter used in much of the test work so far completed is approximately 0.25 seconds. Thus the minimum sampling frequency of 40 samples/sec, selected on the basis of reducing aliasing errors, is much larger than the break frequency associated with this time constant and should give sufficient accuracy.

5.2.2 Low Pass Numerical Filter For Smoothing Digital Data

The recorded flow data was found to have noise of small magnitude at frequencies slightly higher than the frequencies of interest. This noise became greatly amplified when the lag correction was made for a flow measuring system which had a time constant that was large relative to the cyclic period of the noise. In order to reduce the noise component of the flow readings, a numerical filter presented by Ormsby³ was employed in the data reduction computer code. The filter is based on the linear weighting operation given below for continuous time data. This operation relates the input $S(t)$ to the output, $S^*(t)$, by means of a transfer function $h(t)$ with finite time limits T_L, T_U .

$$S^*(t) = \int_{-T_L}^{T_U} h(\xi) S(t - \xi) d\xi \quad (5-4)$$

For discrete or time sampled data, the expression for a linear numerical filter is

$$S_m^* = \sum_{n=-L}^U h_n S_{m+n} \quad (5-5)$$

where

h_n are the filter weights, S_{m+n} are the input samples, and S_m^* are the output samples.

The filter weights are derived from the time-sampled version of the inverse Fourier transform of the proposed frequency function. The resultant frequency function associated with a finite set of weights is then a least square fit to the proposed frequency function. Figure 5-6 shows the type of frequency function, $H(\omega)$, for which the filter weights were derived. This frequency function has unity gain and zero phase shift in the pass band with a p^{th} order polynomial roll-off between the pass ($\omega \leq \omega_c$) and rejection ($\omega \geq \omega_T$) bands.

The $H(\omega)$, corresponding to Figure 5-6, may be specified as:

$$H(\omega) = \begin{cases} 0 & ; |\omega| > \omega_T \\ 1 & ; |\omega| \leq \omega_c \\ \left(\frac{1}{\omega_T - \omega_c}\right)^P (\omega + \omega_T)^P & ; -\omega_T \leq \omega < -\omega_c \\ \left(\frac{1}{\omega_T - \omega_c}\right)^P (\omega - \omega_T)^P & ; \omega_c < \omega \leq \omega_T \end{cases} \quad (5-6)$$

The time domain function (weighting function) $h(t)$ associated with $H(\omega)$ is given by the inverse exponential Fourier transform of $H(\omega)$,

$$h(t) = \int_{-\infty}^{\infty} e^{j\omega t} H(\omega) \frac{d\omega}{2\pi} \quad (5-7)$$

A filter with first order roll-off ($P = 1$) was used in this application because of the increased complexity of the expression for the weights with a higher order roll-off. For the case $P = 1$, equations (5-6) and (5-7) give:

$$h(t) = \frac{\cos \omega_c t - \cos \omega_T t}{\pi(\omega_T - \omega_c) t^2} \quad (5-8)$$

The weights, h_n , in sample space can be evaluated directly from $h(t_n) \Delta t$ where equidistant samples ($\Delta t = \text{constant}$) are assumed. Using $h_n = h(t_n) \Delta t$, $t_n = n\Delta t$, and $\Delta t = 1/f_s$ equation (5-8) gives

$$h_n = \frac{\cos 2\pi n \lambda_c - \cos 2\pi n \lambda_T}{2\lambda_R (\pi n)^2}, \quad \begin{cases} n = 0, \pm 1, \dots, \pm N \\ \lambda_T = \lambda_c + \lambda_R \end{cases} \quad (5-9)$$

where the normalized frequency variable $\lambda = \omega/\omega_s$ has been introduced so that

$$\lambda_c = \omega_c/\omega_s$$

$$\lambda_T = \omega_T/\omega_s$$

$$\lambda_R = \frac{\omega_T - \omega_c}{\omega_s}$$

ω_s = effective angular sampling frequency

The selection of the cutoff frequency, ω_c , depends on the expected noise spectrum and the signal frequencies of interest. The highest frequency of interest in the flow data is approximately 10 cps. Therefore a cutoff frequency between 10 cps and 20 cps will pass the desired component of the flow data and filter out the higher frequency noise.

Selection of the sampling frequency, ω_s , roll-off termination frequency, ω_T , and N (where, $2N+1$ = number of filter weights) depends mainly on the acceptable filter error.

The sampling frequency, itself, should be at least twice the highest assumed signal frequency to prevent frequency aliasing errors in the filter. Since electronic low pass filters with a cutoff frequency of 20 cps were used in the A/D conversion, the highest expected signal frequency should be approximately 20 cps. Thus a sampling frequency of 40 cps or greater is adequate for the numerical filter.

Figure 5-7 taken from reference 2, shows curves of constant error as a function of N and the roll-off parameter, λ_R . An empirical relationship which approximates these curves is:

$$\lambda_R N = \frac{0.012}{\epsilon} \quad (5-10)$$

where ϵ is the percentage error.

For $\omega_c = 20$ cps, $\omega_T = 25$, $\omega_s = 40$ cps, and $N = 50$, the maximum filter error is approximately $\epsilon = 0.2\%$. Thus a filter having parameters in the range of these values should have sufficient accuracy for present purposes.

The final selection of cutoff and terminal frequencies to be used in filtering flow data depends on the magnitude and frequency of noise encountered, which, in general, may differ from one test to another.

ω_c = CUTOFF FREQUENCY (ANGULAR) = $2\pi f_c$
 ω_T = FILTER ROLL-OFF TERMINATION FREQUENCY

Figure 5-6. Frequency Function Used for Linear Numerical Filter

Figure 5-7. N Versus λ'_R , Filter Error Curves

Appendix A

DERIVATION OF ZERO-ORDER DATA HOLD OPERATOR AND LAG CORRECTION EQUATION

The sampled data model of the system to be considered is shown in Figure 5-4. The essential component in this system is the zero-order data hold operator which replaces the continuous input with a series of step approximations. The derivation of the transfer function for a zero-order data hold operator is included in this appendix with the derivation of the lag correction equation.

A.1 DERIVATION OF THE ZERO-ORDER DATA HOLD TRANSFER FUNCTION

The transfer function of a linear system is the Laplace transform of the impulse response of the system. In this case the sampled input to the system, $X^*(t)$, can be represented by a series of impulses at equally spaced time intervals T as shown in Figure A-1. Thus the sampled input is given by

$$X^*(t) = X(t) \delta(t, nT) \quad (A-1)$$

where

$X^*(t)$ = sampled input

$X(t)$ = continuous input

$\delta(t, nT)$ = dirac-delta (unit impulse) function at time, nT .

n = time index = 0, 1, 2, 3, ...

The desired response of the data hold also shown in Figure A-1 is a series of steps having the same height as the corresponding impulse, $X(t) \delta(t, nT)$. Therefore, it can be seen that the desired response of the system to a unit impulse is a unit-magnitude continuous function which is maintained until the end of the sampling interval when its value falls to zero, as shown in Figure A-2.

To obtain the transfer function of this system, the impulsive response can be decomposed into two unit step functions, as shown in Figure A-3. The impulsive response is given by

$$g(t) = u(t) - u(t - T) \quad (A-2)$$

where $u(t)$ is the unit step function. The Laplace transform of $g(t)$ is,

$$G(s) = \frac{1 - e^{-Ts}}{s} \quad (A-3)$$

which is just the transfer function of the zero-order data hold operator.

A.2 DERIVATION OF LAG CORRECTION EQUATION

The output, $\tilde{Y}(s)$, of the sampled data system shown in Figure 5-4 is given by

$$\tilde{Y}(s) = G(s) H(s) X^*(s) \quad (A-4)$$

where

- $\tilde{Y}(s)$ = Continuous output of system
 $G(s)$ = Transfer function of zero-order data hold operator
 $H(s)$ = Transfer function of lag network
 $X^*(s)$ = Sampled input

From Section 5.2.1, the transfer function for the first order lag of the turbine meter frequency converter is

$$H(s) = \frac{1}{\tau s + 1} \quad (\text{A-5})$$

It is more convenient at this point to make a transformation to z space. The z-transformation is applicable to sampled-data systems and is entirely analogous to the Laplace transformation and its application to continuous systems. The z-transform² is

$$F(z) = \sum_{\substack{\text{Poles} \\ \text{of } F(p)}} \text{residues} \left[F(p) \left(\frac{1}{1 - e^{pT} z^{-1}} \right) \right] \quad (\text{A-6})$$

Where $F(p)$ is the Laplace transform of the function $f(t)$ being sampled, evaluated at the pole location $s=p$.

The sampled output in z space, $Y^*(z)$, for the system shown in Figure 5-3 is

$$Y^*(z) = Z[G(s) H(s)] X^*(z) \quad (\text{A-7})$$

where $Z[G(s) H(s)]$ is the z transform of the combined system transfer function $G(s) H(s)$.

The z transformation, $Z[G(s) H(s)]$, can be determined by substituting the expression for $G(s) H(s)$ in Laplace space into equation (A-6) or by using tables of z transforms as in reference 2:

$$Z[G(s) H(s)] = Z \left[\frac{1 - e^{-Ts}}{s(\tau s + 1)} \right] = Z \left[\frac{1/\tau (1 - e^{-Ts})}{s(s + 1/\tau)} \right] \quad (\text{A-8})$$

Using a table of z transforms:

$$Z[G(s) H(s)] = \frac{(1 - e^{-T/\tau}) Z^{-1}}{1 - e^{-T/\tau} Z^{-1}} \quad (\text{A-9})$$

Substituting (A-9) into (A-7) and multiplying by $(1 - e^{-T/\tau} Z^{-1})$ gives,

$$(1 - e^{-T/\tau} Z^{-1}) Y^*(z) = (1 - e^{-T/\tau} Z^{-1}) X^*(z) \quad (\text{A-10})$$

Now taking the inverse z transform of both sides of (A-6) using tables of z transforms yields,

$$Y^*(nT) - e^{-T/\tau} Y^*[(n+1)T] = (1 - e^{-T/\tau}) X^*(nT) \quad (\text{A-11})$$

defining,

$$y_n \triangleq Y^*(nT), y_{n+1} \triangleq Y^*[(n+1)T] = \text{Sampled output in t space at time } t = nT, (n+1)T \text{ respectively}$$

$x_n \triangleq X^*(nT)$ = Sampled input in t space at time $t = nT$

Rearranging (A-11) and expressing as a recursion relationship gives,

$$x_n = \frac{1}{(1 - e^{-T/\tau})} \left[y_{n+1} - e^{-T/\tau} y_n \right] \quad (\text{A-12})$$

which is the desired result for numerically removing the lag introduced by the low pass filter $1/(rs + 1)$.

Figure A-1. Step Approximation of Continuous Input

Figure A-2. Impulsive Response of a Zero-Order Data Hold Operator

Figure A-3. Step-Function Components of Impulsive Response of Zero-Order Data Hold

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